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U.S. Department of Energy Workshop Report: Research Needs for Wind Resource Characterization

Technical Report
NREL/TP-500-43521
June 2008

Jointly Sponsored by:

DOE Office of Science, Office of Biological and Environmental Research

and

DOE Office of Energy Efficiency and Renewable Energy, Wind & Hydropower Technologies Program

Co-Chairs:
S. Schreck, J. Lundquist, and W. Shaw

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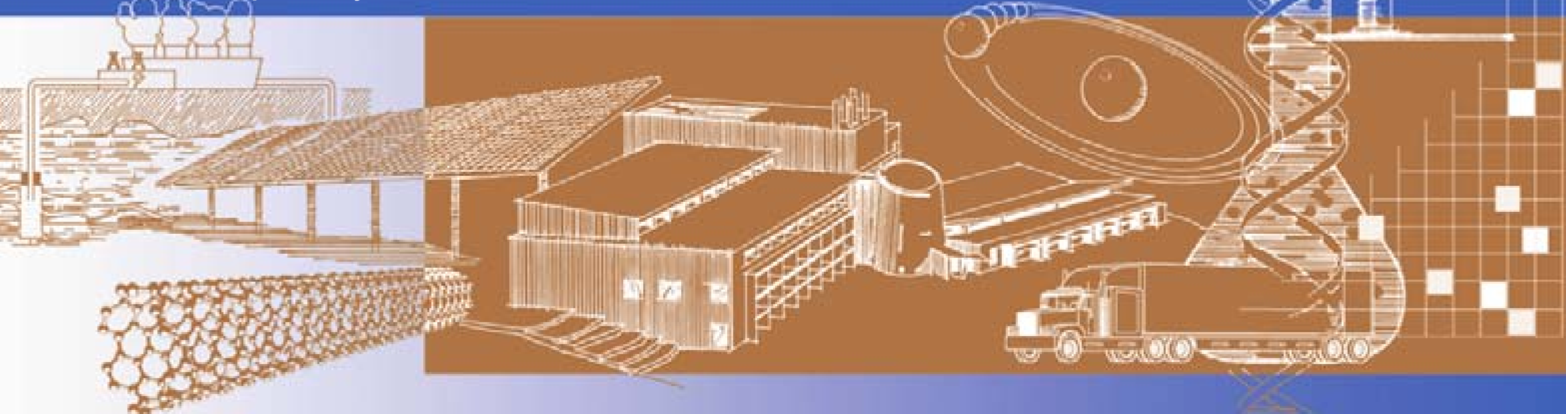

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Prepared under Task No. WER7.0201

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Contract No. DE-AC36-99-GO10337

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January 14 – 16, 2008

Broomfield, Colorado

U.S. Department of Energy Workshop Report

Research Needs for Wind Resource Characterization

Co-Chairs
Julie Lundquist, Lawrence Livermore National Laboratory
Scott Schreck, National Renewable Energy Laboratory
William Shaw, Pacific Northwest National Laboratory

DOE Office of Biological and Environmental Research
Rickey Petty, Program Manager
Ashley Williamson, Program Manager

DOE Office of Energy Efficiency and Renewable Energy
Sam Baldwin, Chief Technology Officer

Administration
Stacey Burge, National Renewable Energy Laboratory
Bruce Green, National Renewable Energy Laboratory

Report Publication and Website
National Renewable Energy Laboratory

Recommendation Panel Chairs and Authors

Turbine Dynamics Panel
Co-Chaired by Scott Schreck, NREL; and Larry Carr, US Army AMRDEC

Isolated Turbine Inflow Characterization
Jonathon Naughton, University of Wyoming

Ingestion of Wake from Upwind Turbines
Scott Schreck, NREL

Extreme and Anomalous Inflow Events
Jason Jonkman, NREL

Micrositing and Array Effects Panel
Chaired by Pat Moriarty, NREL

Improved Wake Models
Rebecca Barthelmie, Edinburgh University / Indiana University

Planetary Boundary Layer Research and Development
Edward Patton, NCAR

Acquiring and Exploiting Large-Scale Data Sets
Patrick Moriarty, NREL

Technology Transfer and Tool Integration
Patrick Moriarty, NREL

Mesoscale Processes Panel
Chaired by Walter Bach, ARO

Wind Energy Testbed Development
Jim Wilczak, NOAA
Al Germain, BP Alternative Energy

Improve Industry and Atmospheric Modeling
Bob Banta, NOAA,
Jerome Fast, PNNL

Create and Convene a Cooperative Working Group
Walter Bach, Army Research Office
Tom Acker, Northern Arizona University

Climate Effects Panel
Chaired by Ruby Leung, PNNL

Improve Quantification and Identify Causes of Historical Change and Variability of Wind Resources
Jeff Freedman, AWS True Wind
Darko Koracin, Desert Research Institute
Gene Takle, Iowa State University
Sara Pryor, Indiana University

Improved Quantification of Future Changes in the Mean and Variability of Wind Climates/Resources
Sara Pryor, Indiana University
Ruby Leung, PNNL
Darko Koracin, Desert Research Institute
Dora Yen Nakafuji, LLNL/California Energy Commission

Interactions Between Wind Plants and Local, Regional, and Global Climates
Gene Takle, Iowa State University
Manda Adams, University of Calgary
Steve Chin, LLNL

List of Acronyms

ABL – Atmospheric Boundary Layer
ACARS – Aircraft Communications Addressing and Reporting System
AIAA – American Institute of Aeronautics and Astronautics
AOGCM – Atmosphere-Ocean General Circulation Models
ARM – Atmospheric Radiation Measurement
ASCOT – Atmospheric Studies in Complex Terrain
ASME – American Society of Mechanical Engineers
ASOS/AWOS – Automated Surface/Weather Observation System
AWEA – American Wind Energy Association
BEM – Blade Element Momentum
CASES-99 – Cooperative Atmosphere-Surface Exchange Study 1999
CFD – Computational Fluid Dynamics
DES – Detached Eddy Simulation
DNS – Direct Numerical Simulation
GBRS – Ground-Based Remote Sensing
IEC – International Electrotechnical Commission
IPCC – Intergovernmental Panel on Climate Change
LES – Large Eddy Simulation
LIDAR – Light Detection and Ranging
LTER – Long Term Ecological Research
MEMS – Microelectromechanical Systems
NWP – Numerical Weather Prediction
NCAR – National Center for Atmospheric Research
NCDC – National Climatic Data Center
NARCCAP – North American Regional Climate Change Assessment Program
PBL – Planetary Boundary Layer
PCMDI – Program for Climate Model Diagnosis and Intercomparison
RANS – Reynolds Averaged Navier-Stokes
SODAR – SOnic Detection And Ranging
VAD – Velocity Azimuth Display
WAsP – Wind Atlas Analysis and Application Program
WRF – Weather Research and Forecasting model

Executive Summary

The U.S. Energy Information Agency estimates that our nation's electricity demand will rise by 39 percent in the years 2005 to 2030 and will reach 5.8 billion megawatt-hours by 2030. At present, wind energy provides approximately 1 percent of total U.S. electricity generation. To produce 20 percent of that electricity, U.S. wind power capacity will need to exceed 300 gigawatts, corresponding to an increase of more than 285 GW over 2007 levels. A recent analysis (available at: http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf) by the U.S. Department of Energy (DOE), National Renewable Energy Laboratory (NREL), and American Wind Energy Association (AWEA) demonstrated the feasibility of expanding the U.S. wind industry to this level. While the 20 percent wind scenario is not a prediction of the future, it does represent a plausible scenario for wind energy in the U.S. electricity generation portfolio.

To exploit these opportunities and address attendant problems, a workshop concentrating on Research Needs for Wind Resource Characterization was convened during January 14 – 16, 2008 in Broomfield, Colorado. This event was organized collaboratively on behalf of two DOE organizations; the Office of Biological and Environmental Research (OBER) and the Office of Energy Efficiency and Renewable Energy (EERE). This workshop had two purposes. First, it brought together select researchers from the atmospheric science and wind energy engineering communities to identify leading problems in these two areas. Second, it solicited recommendations from these experts regarding productive future DOE research thrust areas. Ultimately, the workshop was attended by over 120 atmospheric science and wind energy researchers, from industry, academia, and federal laboratories in North America and Europe.

To provide a framework for the workshop, four focus areas were delineated: 1) Turbine Dynamics, 2) Micrositing and Array Effects, 3) Mesoscale Processes, and 4) Climate Effects. These areas were introduced in four plenary presentations delivered by internationally recognized experts representing these fields. Participants then joined one of three "Problem Definition" breakout groups to address these focus areas. Each group included participants from the atmospheric science and wind energy engineering communities to promote knowledge exchange between the two. After the Problem Definition groups had addressed each of the four focus areas, participants then joined one of four "Recommendation" breakout groups aligned with their individual expertise to distill the problem definition discussions into a cohesive set of research thrust recommendations. The resulting research thrust recommendations are documented in detail in the following report, and summarized below.

Workshop discussions made it clear that research in each of the four focus areas had developed in relative isolation from the others. The nonlinear fluid mechanic character underlying these areas compelled this compartmentalization to achieve tractability, and the physical separation in spatial and temporal scales generally facilitated success. However, one major theme that emerged from the workshop was that continued progress in wind energy technology would require interdisciplinary unification with the atmospheric sciences to exploit previously untapped synergies. A second major theme that emerged from the workshop was the need to apply experiments and observations in a coordinated fashion with computation and theory. In addition to these two comprehensive recommendations that were common to all four focus areas, specific recommendations were delineated for each focus area.

In the Turbine Dynamics focus area, detailed characterizations of inflows and turbine flow fields were deemed crucial to attaining the accuracy levels in aerodynamics loads that will be required for future machine designs. To effectively address the complexities inherent in this area, an incremental approach involving hierarchical computational modeling and detailed measurements was recommended, wherein the isolated turbine would be considered initially, and then the ingestion of a wake trailed from an upwind turbine would be addressed. In addition, a third thrust was recommended that would entail modeling extreme and anomalous atmospheric inflow events as well as the aerostructural responses of turbines immersed in these events.

The Micrositing and Array Effects focus area considered improved wake models to be important for more accurately characterizing energy capture losses and higher turbulence downwind of large, multiple row wind plants. Planetary boundary layer R & D was deemed necessary to achieve accurate, reliable determination of inflow mean structure and turbulence statistics in the presence of various atmospheric stability effects and complex land-surface characteristics. Finally, a requirement was identified for acquiring and exploiting large-scale wind inflow data sets, which will need to cover heights to 200 m and satisfy high spatial and temporal resolution requirements unique to wind energy needs.

The Mesoscale Processes focus area deemed improvements in fundamental understanding of mesoscale and local flows crucial to providing enhanced model outputs suited for wind energy production forecasts and wind plant siting. This improved understanding would be exploited by developing wind forecasting technologies well suited to wind plant siting and operations. Modeling approaches must be developed to resolve spatial scales in the 100-m to 1000-m range, a notable gap in current capabilities. Validation of these models will require development and deployment of new instruments and observational strategies, including additional analyses of existing measurements and additional longer-term measurements.

In the focus area of Climate Effects, theoretical, numerical, and observational work was recommended to identify and understand historic trends in the variability of wind resources to increase confidence in resource estimation for future planning and validation. For the same reasons, similarly multifaceted research was suggested to improve quantification of future changes in the mean and variability of wind climate and resources. Workshop participants also considered it important to characterize interactions between wind plants and local/regional/global climates through modeling and observations aimed at the physical link between wind plants and atmospheric boundary layer dynamics.

High-penetration wind energy deployment to meet long range U.S. energy goals represents a daunting though attainable and crucial national objective. Meeting these goals will require an unprecedented ability to characterize the operation of large wind turbines deployed in gigawatt wind plants and extracting elevated energy levels from the planetary boundary layer. Success will demand accurate, reliable computations and measurements across an expansive scale range that extends from microns to kilometers. Assets residing within the DOE national laboratory complex, allied with researchers from industry and academia, represent a formidable capability for realizing these objectives. Together, these resources will lay the foundations for a challenging collaborative research agenda of wind resource characterization in support of aggressive wind energy deployment to meet strategic U.S. energy needs.

Contents

1. Introduction and Background

1.1. Wind Energy Prospects

The U.S. Energy Information Agency estimates that our nation's electricity demand will rise by 39 percent in the years 2005 to 2030, and will reach 5.8 billion megawatt-hours by 2030. To produce 20 percent of that electricity, U.S. wind power capacity will need to exceed 300 gigawatts, corresponding to an increase of more than 285 GW over 2007 levels. A recent analysis by the DOE, NREL and the American Wind Energy Association (AWEA) demonstrated the technical feasibility of expanding the U.S. wind industry to this level (http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf). While the 20 percent wind scenario is not a prediction of the future, it does represent a plausible scenario for the role of wind energy in the U.S. electricity generation portfolio.

In 2006, wind energy production costs ranged from 5 to 8.5 cents per kWh (before any reduction by the federal production tax credit, at 1.9 cents/kWh in 2006). Since 2004, turbine costs have increased due to strong demand for new wind equipment, commodity price increases for materials like steel and copper, and the weakening U.S. dollar. As wind energy continues to successfully confront these difficulties, it is clear that research and development has enabled wind to become and remain a viable power source in today's energy market. Nonetheless, wind energy still provides less than 1 percent of total U.S. electricity generation. Accelerating deployment and further improving cost effectiveness will entail a combination of reducing initial, operations and maintenance, and replacement costs, while maintaining or increasing energy capture.

Various risks threaten the U.S. wind industry's ability to meet this challenge. Wind plant performance, in terms of revenues and operating costs, compared with the projections used in financing will drive the risk level of future installations. In addition, risk associated with introducing new technology at the same time that manufacturing is scaling up and production is accelerating to unprecedented levels will be substantial. Before turbine manufacturers can stake the next product on a new feature, performance of that innovation needs to be firmly established and durability needs to be characterized as well as possible. The consequences of these risks both directly affect the revenues of wind equipment manufacturers and wind plant operators, and indirectly affect the continued growth of investment in wind. Direct impacts include increasing operations and maintenance costs, poor availability driven by low reliability, and poor wind plant array efficiencies. Indirect impacts include increased cost of insurance and financing, slowing or stopping development, and loss of public support.

1.2 Workshop Motivation

Ultimately, investment in wind resource characterization research aimed at improving wind turbine and wind plant performance while mitigating risk and uncertainty holds the potential to save billions of dollars in energy costs annually with a U.S. power generation portfolio that includes 20 percent wind. To exploit these opportunities and address attendant problems, a workshop focusing on research needs for wind resource characterization was convened during January 14 – 16, 2008, in Broomfield, Colorado. This event was organized collaboratively on behalf of two DOE organizations, the Office of Biological and Environmental Research (OBER) and the Office of Energy Efficiency and Renewable Energy (EERE).

This workshop had two purposes. The first was to bring together select researchers from the atmospheric science and wind energy engineering communities to survey the state of the art and identify leading problems in these two areas. The second was to solicit recommendations from the assembled scientific and technical community regarding potentially productive future DOE research thrust areas. The results of this workshop are documented in the following report.

1.3 Report Structure

Immediately following the current section, abbreviated summaries of research thrust recommendations are presented for the four workshop focus areas of turbine dynamics, micrositing and array effects, mesoscale processes, and climate effects. Preceding these summaries of individual research thrust recommendations are synopses of two research themes that emerged repeatedly throughout the workshop. In addition to the several research related summaries, three recommendations for organization and process within the wind engineering and atmospheric science communities are summarized. Finally, after some brief remarks to conclude the condensed portion of the report, four to six-page reports offering considerably greater detail for each research thrust recommendation are presented. Comprising the report appendices are a description of workshop logistics, the workshop agenda, and a list of attendees.

2. Summary of Recommendations

2.1 Cross-Cutting Research Themes

Two common themes emerged as recommended research thrusts from across the spatio-temporal scales discussed at the workshop: the need for **observations** for model improvement and validation, and the need for improved **modeling capabilities, which span spatio-temporal scales from those associated with wind turbine dynamics to those pertaining to climate effects**. This convergence of scientific and technical needs provides opportunities for leveraging investments and encouraging collaboration across spatio-temporal scales. For example, any investment in collecting observations required for advances in one area will likely contain the possibility that, for an additional incremental cost, the scientific needs of other communities can be addressed as well. Additionally, many of the modeling research thrust recommendations recognized that, for scientific progress to occur, integrated approaches, which bridge spatio-temporal scales, are required. Maximizing this opportunity will require integrated planning between the mesoscale/climate research communities and the turbine-scale/micrositing research communities.

2.1.1 Acquire observations for model validation and improvement

Each of the four focus areas – turbine dynamics, micrositing and array effects, mesoscale processes, and climate effects – identified an outstanding need for integrated datasets that offer information for developing and validating models of their respective domains. These integrated datasets include profiles of wind measurements, as well as characterization of atmospheric stability and the necessary information to characterize the site where the observations are collected, through diurnal and seasonal cycles. Most wind turbines reside in the lowest portion of the planetary boundary layer, from the surface to about 200 m above the surface. Although there are networks of wind speed observations at 10-m heights, these observations are not representative of the vertical profile complexity of wind and atmospheric stability which are needed for improved turbine structural design, for forecasting wind resources on short and long timescales, or for understanding the relationship between wind plants and climate change, both local and global. Additionally, because wind plants are and will be deployed in diverse regions, including complex terrain and offshore situations, observations representative of these multiple regions throughout the diurnal and seasonal cycles are required. The DOE Atmospheric Radiation Measurement program provides a good example for such long-term measurements.

2.1.2 Improve modeling capabilities across scale range

Critical areas for model improvement and validation have been identified within each of the four spatio-temporal focus areas (turbine dynamics, micrositing and array effects, mesoscale processes, and climate effect), as well as in the "terra incognita" between these scales. For example, to understand the effects of turbine wakes on downwind turbines and the downwind microclimate, simulation tools are needed which can quantify turbine wakes, the evolution of the background atmosphere, and the interaction of the atmosphere with the surface. Therefore, this problem requires scientific expertise and development in the turbine scale, the micrositing scale, and the mesoscale focus areas, and the application is relevant to the climate-scale focus area. It is critical to acknowledge that many of the modeling research thrusts identified in this workshop span the spatio-temporal focus areas. Therefore, successful and productive scientific efforts to address these needs must integrate expertise across these spatio-temporal scales rather than promoting isolated development within each scale separately.

To maximize positive impact on the wind industry, the following measures should be taken to facilitate transition of these scientific advances to engineering application.

- Computational methodologies should be taken from the turbine dynamics, micrositing and array effects, mesoscale processes, and climate effects areas and integrated into appropriate tools. Considerations like resolution, reliability, and accuracy will need to be balanced against those like complexity, resource requirement, and turnaround time.
- Uncertainties in the individual models as well as the resulting integrated model need to be carefully quantified, documented, and, to the extent possible, mitigated.

2.2 Turbine Dynamics Summary

The Turbine Dynamics focus area identified and documented three research thrust recommendations: 1) Isolated turbine inflow characterization, 2) Ingestion of wake from an upwind turbine, and 3) Extreme and anomalous inflow events. These recommendations are summarized below.

2.2.1 Develop accurate models for isolated turbine inflow characterization

Currently, detailed inflow information is lacking, even for turbines operating in isolation from other turbines or wind plants. Crucial inflow information includes mean wind speed, horizontal and vertical shears, and turbulent velocity fields across the rotor swept area. Overall, these shortcomings limit accurate prediction of rotor loads, energy production, and machine lifetime during wind turbine design. Clear understanding and detailed characterization of the physical parameters that govern turbine inflows would enable construction of more accurate, reliable turbine inflow models. A hierarchy of computational models will be crucial for successfully characterizing these turbulent inflows, including large eddy simulation models. Requisite model validations will entail data with temporal and spatial resolution sufficient to capture turbulence scales pertinent to turbine inflows and aerodynamics. These data will need to be of sufficient duration and frequency to document variations in inflow conditions through cycles of varying periods (diurnal, seasonal, etc.). Achievement of this inflow modeling capability will enable more accurate prediction of loads, energy production, and lifetime during the design process. This, in turn, will reduce uncertainty in deployed performance, help decrease finance costs, and drive down wind energy costs.

2.2.2 Develop models to characterize ingestion of wakes from upwind turbines

Wind turbine vortical wakes persist over significant distances, and impinge on downwind turbines in wind plant arrays. While atmospheric inflows alone present significant physical complexities, addition of turbine wakes containing distributed vorticity and concentrated vortices will require that a more expansive range of spatial and temporal scales be characterized. Efficient resolution of the full range of pertinent scales will require a hierarchical modeling suite combined with adaptive gridding. In a similar manner, measured validation data must adequately resolve distributed vorticity and cohesive vortices in addition to atmospheric structures. Combined with other types of instrumentation, three-dimensional scanning LIDARs (LIght Detection and Ranging) will provide the spatial coverage and resolution needed to acquire these data. In addition to field testing, it is likely that carefully targeted experiments in large wind tunnels will be useful for acquiring measurements under controlled conditions not possible in the field environment. This inflow modeling capability will furnish more accurate prediction of loads, energy capture, and lifetime for turbines deployed in wind plants. This, in turn, will reduce uncertainty in deployed performance, help decrease finance costs, and drive down wind energy costs.

2.2.3 Characterize extreme and anomalous inflow events

Concentrated wind gusts, rapid wind direction changes, or passage of energetic atmospheric structures impose critical loads on wind turbines. These extreme events expend turbine fatigue life, cause component failures, and can even threaten catastrophic machine failure. Advanced Reynolds averaged Navier-Stokes (RANS) and large eddy simulation (LES) atmospheric models likely can provide more spatially detailed, time-accurate representations of atmospheric events. These can then be coupled with turbine aeroelastic models to predict the impact of these extreme events on wind turbine structures and operation. Measured data, having required resolution in time and space, could be acquired via current 1-D or future 3-D scanning LIDARs. In addition, data from current atmospheric measurement systems could be examined using methodologies appropriate to detecting and characterizing events considered extreme or anomalous by the wind energy community. Ultimately, comprehension of these events could enable real-time sensing and control response, to mitigate impacts on operating turbines. These measures would improve deployed turbine reliability, directly decreasing operations and maintenance costs and increasing energy capture through reduced downtime.

2.3 Micrositing and Array Effects Summary

Two issues identified as relevant to power plant performance were micrositing and array effects. These are of particular importance for wind plants that are large, sited in complex terrain, or subject to unique atmospheric phenomena. Micrositing refers to changing the particular location of a turbine with respect to the terrain or local inflow to increase energy capture, or to reduce inflow turbulence and the adverse loads it generates. Array effects consist of blockage and wake influences, both of which originate with individual turbines and are aggregated across entire wind plants. In either case, wake effects result in decreased inflow speeds and energy capture, and higher turbulence levels and fatigue loading.

2.3.1 Construct improved wake models

Power losses due to reduced flow behind individual turbines and higher turbulence (wakes) lead to problems optimizing array spacing. Wind plant models appear to make reasonable predictions of power losses due to wakes in small wind plants (less than 3 – 4 rows). However, large offshore wind plant experience shows a very large discrepancy exists between standard predictions of the average power loss due to wakes which are 10 to 15 percent of total average power and those which have been observed. In large wind plants in complex terrain, it is postulated that similar discrepancies exist. In brief, the most urgent research needs are:

- Energy capture losses in large wind plants are under-predicted, and improper wake modeling is a likely source. The scale and cause of this problem should be assessed.
- The effect of wakes on fatigue loads is unclear over project lifetimes. The impact of wakes on turbine loads is significant but needs to be quantified.
- The effect of wind plants on each other is unclear. As multiple clusters of wind plants are developed within 20 km of each other, particularly offshore, tools to evaluate the impact or shadowing effect of one wind plant on a nearby wind plant are needed.
- Turbulence/load effects and power production estimates are often uncoupled and are not yet incorporated into current models. These two computations are the critical components of the next generation models to optimize wind turbine spacing which will maximize energy output and minimize loads for a given site or area giving optimal energy costs and project lifetimes.

2.3.2 Advance planetary boundary layer research and development

As determined by current and future rotor swept areas, improved understanding and prediction of the planetary boundary layer (PBL) between heights of 50 m and 200 m will hold central importance for the wind industry. Accurate, reliable determination of inflow mean and turbulence statistics will entail characterization of atmospheric stability effects, as well as impacts due to orography and land-surface characteristics. Improved predictions of wind shear, extreme winds, and turbulent fluctuations will enable improved design predictions of fatigue and extreme loads, and will provide direct guidance for individual turbine micrositing and overall wind plant array placement to preclude underperformance issues. The following areas will be crucial to achieving these objectives.

- Instrumentation and techniques need to be developed for observing the 50 - 200-m portion of the lower atmosphere and acquiring data pertinent to micrositing and array issues. These data likely will encompass a timescale range and involve levels of accuracy and precision greater than those generally required for standard weather forecasting.
- Atmospheric boundary layer parameterizations of surface flux phenomena need to be generalized, to relax constraints associated with assumptions of spatial homogeneity, and to provide more detailed estimates of fluctuating and mean inflow components under varying stability conditions. This likely will entail higher fidelity representations of multi-faceted surface layer physics in the presence of pronounced near-surface horizontal/vertical gradients.
- More capable modeling methodologies are needed for characterizing the combined effects of complex terrain, ground cover, heat transfer, and wind turbine presence. Computational resource growth will enable use of direct numerical simulation (DNS) and LES algorithms, and could lead to embedding these within mesoscale models like NCAR's Weather Research and Forecasting (WRF) model. At the same time, resource limitations will secure a niche for subgrid modeling techniques.

- Appropriately resolved observations will be needed for understanding the physics that govern planetary boundary layer, micrositing, and array effects. These observations will need to be carried out in locations/conditions representative of existing and planned wind plants. To achieve this, a balance must be found between detailed, short-term characterizations at numerous sites and extended campaigns at fewer locations.

2.3.3 Acquire and exploit large-scale data sets

Both industry designers and laboratory researchers need reference data sets of higher quality and for a broader range of conditions than those available at present, to better quantify the mechanisms that govern the conversion of wind inflow to mechanical energy. Pertinent data sets will be unique to wind energy since current utility-class wind turbines operate in a region of the atmosphere (50 – 200 m above ground) that has not been thoroughly studied and remains poorly understood. In addition, the requirements for spatial and temporal resolution needed to characterize and understand detailed turbine-atmosphere interactions are more stringent than current data sets can provide.

- Existing manufacturer, developer, or operator data that pertain to wind plant or wind turbine operation need to be assembled in a common repository with a standard format, and made broadly accessible. In addition to technical issues like data quality, formatting, and archiving, legal issues associated with intellectual property or competitive position will need to be resolved.
- A network of measuring sites needs to be created to acquire new reference data. These sites should be located near substantial wind resources, where wind plants currently exist or are likely to exist in the future. Certain sites with interesting atmospheric (e.g. low-level jet in the Great Plains) or turbine behavior might be better resolved in space or time, or measured for extended periods.
- Computational methods will be useful adjuncts for acquiring new data, and essential elements for exploiting data. To reduce measurement campaign time and expense, computational tools can be used to design and optimize experiments. Once data have been acquired, data mining techniques will facilitate extracting meaningful information from the large-scale data sets. Finally, physics-based computational methodologies can be applied to compensate for shortcomings in spatial or temporal resolution.
- As atmospheric data are acquired and exploited, deficiencies in understanding and gaps in data will become apparent. When atmospheric measurements are deemed infeasible for addressing these shortcomings, appropriately designed wind tunnel experiments may offer an alternative.

2.4 Mesoscale Processes Summary

The Mesoscale Processes group identified one administrative recommendation; to convene an industry-research working group, and two research thrust recommendations; to establish and support a Wind Energy Testbed to provide datasets for characterization of the atmospheric boundary layer for wind energy applications, and to improve industry and research modeling capabilities relevant to the atmospheric boundary layer. Participant input regarding these recommendations are included in this report. The scientific research thrusts raised by the Mesoscale Processes working group span the following three general areas:

1) Improvements in Fundamental Understanding of Mesoscale and Local Flows,
2) Development of Wind Forecasting Technologies for Siting and for Adaptive Operation, and
3) Development and Deployment of New Instruments and Observational Strategies.

2.4.1 Improve fundamental understanding of mesoscale and local flows

The current generation of numerical weather prediction (NWP) models exhibits skill in predicting the synoptic weather for conventional purposes. However, the parameters critical for wind energy purposes, such as near-surface wind speeds, wind directions, vertical wind shears between the surface and turbine blade tip, and turbulence, have less impact on routine weather forecasts, and so have not received as much attention as severe weather (precipitation, thunderstorms, hurricanes). These errors in boundary-layer parameters, however, significantly impact the wind energy community, contributing to errors in wind plant siting and energy forecasts. Fundamental knowledge gaps need to be addressed in order to provide improved representation in models of winds, wind shears, and turbulence critical for wind energy activities. New or improved theories based on measurements and simulations are needed for a range of small-scale atmospheric processes. For example, how do boundary-layer phenomena like the nocturnal low-level jet and the resulting wind shear and turbulence affect wind power performance and machine loading? A better understanding of the origin and evolution of these phenomena would enable their prediction on the multiple timescales relevant for wind energy applications.

Areas of research include:

- Low-level jets
- Stable boundary layers
- Surface roughness properties such as canopies and complex terrain topography
- Energy exchange between the surface and the atmosphere.

2.4.2 Develop wind forecasting technologies for siting and adaptive operations

NWP models have not been optimized to address the needs of the wind energy community. In fact, even the spatial scales addressed by these models are inappropriate for wind energy forecasting needs. To predict smaller scale variations in terrain and other surface roughness elements, including the interactions among turbines in wind plants, which affect local wind fields, resolution on spatial scales less than 1 km but greater than 100 m is desired.

Unfortunately, mesoscale models rely on parameterizations valid for grid spacings as small as approximately 1 km, and should not be run at resolutions finer than 1 km because these models' parameterizations are not valid at those scales. Large-eddy simulation (LES) models which employ different turbulence closure methods have been designed for spatial scales less than 100 m. The simulation gap between mesoscale and eddy-resolving models should be bridged to provide local wind variation forecasts for both siting and adaptive operations. In complex terrain, where slopes exceed 30 degrees and many wind turbines are sited, different approaches may be required.

Development, testing, and validation of existing approaches tailored specifically to wind energy applications, such as ensemble modeling and/or data assimilation approaches would be fruitful. These specific developments for forecasting capability would benefit from rapid update cycles and assimilation of turbulence measurements, among others. Finally, efforts should be made to incorporate into forecasting models the ongoing research supported by other agencies' activities, such as advances in cloud processes for improved parameterization of downbursts.

Areas where research is needed include:

- Data assimilation, including assimilation of turbulence observations, with rapid updating
- Parameterization of fundamental processes on scales needed to inform turbine operation
- Development of methods to quantify uncertainties in forecasts for operations
- Improvement in techniques to link computational fluid dynamics (CFD) and LES modeling at the turbine scale with mesoscale and synoptic scale models
- Incorporation of the wake effects of turbines into these forecasting models to inform adaptive operations.

2.4.3 Develop and deploy new instruments and observational strategies

The forecasting technologies and uncertainty quantification described in the previous section will require the development of new observational capabilities and strategies, including additional analyses of existing measurements and additional longer-term measurements. Some of the data required, such as profiles of turbulence between the surface and turbine blade tip, are not currently available with existing technology, although multiple-LIDAR developments show promise in this area. Even when the observations needed are available, the appropriate methods for comparison of point observations with volumetric model output are poorly understood. Previous model evaluations of near-surface vertical gradients in wind speed, direction, and turbulent properties have relied on field campaign measurements made over a short period of time (often less than a month) and at specific sites. However, industry experience indicates that this strategy is inadequate for more generic model applications for all locations and time periods. Therefore, measurements at a variety of wind turbine sites over several years are needed to better assess the performance of current mesoscale model parameterizations and develop improved parameterizations based on new theoretical relationships.

Areas of research need include:

- Development of new measurement technologies and strategies including integrated remote sensing systems
- Improvement in methodologies for comparing model grid values with *in situ* and point measurements
- Characterization of atmospheric flow over multiple seasons and in multiple locations to test theoretical and numerical descriptions of the atmosphere in regions and on time scales critical for wind energy purposes.

2.5 Climate Effects Summary

Climate change has the potential for significant financial consequences within the lifetime of a wind plant. The following research thrust areas address issues of climate effects on wind power production.

2.5.1 Quantify and understand historic trends and variability of wind resources

The magnitude and causes of historic changes in the wind resource are not well defined or understood. This stems from inadequate long-term data and metadata, an inadequate inventory of existing data, and an incomplete understanding of discrepancies in historical trends derived from different data sets. In addition, there is a need to quantify how well currently recognized regional and global climate indices explain wind climates across a range of scales.

Theoretical and numerical efforts that will be required include:

- Assessment of the strengths and weaknesses of current-generation models (global/regional/local) for reproducing trends and variability in the wind resource.
- Development of metrics for model evaluations
- Development of a coordinated set of model experiments to understand wind resources, trends, and variability
- Quantification of the scales of coherent variability of wind speeds (both temporal and spatial) and links to global and regional forcings.

Observational requirements include:

- Creation of an inventory of quality-controlled data sets suitable for wind energy applications
- Development of techniques to analyze data sets for wind resources, especially above the surface
- Comprehensive evaluations of applications of statistical methods for wind extremes.

The expected impacts of this research thrust include increased confidence in resource estimation for future planning and validation, improved understanding of physical mechanisms responsible for trends and variability in wind resources, facilitation of future model development, and reduced risk and uncertainty for investments in wind energy.

2.5.2 Improve predictions of wind resource mean and variability

There is currently no cohesive assessment of future wind climates over the United States. This is a critical need for planning major investments in wind power.

Numerical and theoretical steps required to address this need include:

- Development of new techniques for scale reconciliation (downscaling)

- Performance of multiple global and regional numerical simulations for evaluation of existing downscaling techniques and for facilitating the intercomparison of techniques
- Development of uncertainty estimates and the assessment of major sources of uncertainty
- Archival of appropriate variables and time scales from AOGCM
- Examination of the probability of changes in extreme events relevant to wind energy.

Observational needs include:

- Development of a long-term measurement program to identify future trends; these would especially include measurements of wind shear and boundary layer observations above 10 m.
- Continued and continuous satellite- and surface-based remote sensing data for continued development of observation and analysis techniques.

Efforts in this area will lead to increased confidence in resource estimation for future planning and validation, improved understanding of physical mechanisms responsible for future changes, continuing improvement of modeling capabilities and statistical analysis tools, reduced risk for investments in the wind resource, improved assessment of other climate change impacts, and better recommendations for wind plant design and siting within the context of climate change.

2.5.3 Characterize interactions between wind plants and local/regional/global climates

There is currently considerable uncertainty regarding physical feedback between wind plants and boundary layer dynamics and uncertainty regarding how those feedbacks might interact with or affect climate change. At the same time there are very few observations that could be used to measure the impact of existing wind plants on boundary layer dynamics.

To respond to this issue, the following research activities are needed:

- Development and evaluation of coupled (multi-scale) models that explicitly treat wind plants and incorporate them in mesoscale simulations
- Development and evaluation of appropriate parameterizations of wind plants and other structures that are suitable for inclusion in models
- Development of observational data sets that can be used to quantify the interactions between wind plants and boundary layer properties
- Deployment of existing remote sensing technologies at currently operating wind plants.

The effect of this research thrust will be to better predict the effect of wind plants on the local environment, to better identify optimal spacing of wind plants, and to facilitate comparative analyses of the impact of wind plants relative to other kinds of power plants.

2.6 Organizational and Process Summary

In addition to the scientific research thrusts defined by the working groups, participants articulated three administrative recommendations. All four of the working groups, spanning the spatio-temporal scales from turbine dynamics to climate effects, commented on the perceived utility of the extensive but private meteorological datasets collected by industry participants. The Mesoscale Processes working group called for the continuation of the discussions initiated at this workshop via the establishment of an ongoing industry-research working group.

2.6.1 Enable Data Access and Data Sharing

Principals in the wind energy industry routinely collect large amounts of data – meteorological observations at the turbine and upwind, and amounts of power collected at each turbine in an array, for example – which could be used to understand complex meteorological phenomena and their effects on wind energy, to develop new parameterization approaches, and to test or validate new models. These data are not routinely shared because of intellectual property concerns and concerns over competitive advantages or disadvantages. By defining a quality control standard for such data and creating a legal and/or technical mechanism for data exchange and aggregation, a potentially rich source of data could become available for addressing outstanding scientific and technical questions.

2.6.2 Convene a Cooperative Industry-Research Working Group

This workshop provided a one-time forum for members of the wind industry and meteorological research communities to interact, identify common priorities, and understand the other community's operational capabilities and needs. The numerous common interests and activities of the research and industry communities could be identified and addressed in a coordinated manner via a long-standing cooperative working group. This group would provide guidance for ongoing research efforts and provide a forum to ensure the transfer of technology and understanding from research to industry. Specific short-term tasks could include:

- Generate recommendations on how to best configure current state-of-the-science models (horizontal and vertical resolution, parameterizations) for wind energy applications.
- Address and resolve the intellectual property concerns regarding the "data sharing" recommendation, above.

2.6.3 Facilitate Technology Transfer

Unquantified uncertainties culminate in higher risk for investors, economic penalties to developers for under-producing plants, and a higher cost of energy. More rapid transfer of wind prediction technology from research to industry would enable more accurate predictions for siting and operating wind plants. Efforts should include increased communications between research and industry via special sessions at both industry (e.g., AWEA Windpower or AIAA/ASME Wind Energy Symposium) and academic (e.g., American Meteorological Society's Boundary Layers and Turbulence Meeting) conferences.

2.7 Conclusion

Accomplishing high penetration wind energy deployment goals to meet long-range U.S. energy requirements represents a daunting, though attainable and crucial, national objective. Meeting these deployment goals will require an unprecedented ability to characterize the operation of multi-megawatt wind turbines, deployed in gigawatt wind plants and extracting unprecedented levels of energy from the earth's planetary boundary layer.

From a science and engineering perspective, success will demand accurate, reliable computations and measurements across an expansive scale range that extends from microns to kilometers. OBER and EERE assets residing within the DOE national laboratory complex, allied with researchers from industry and academia, represent a formidable resource for realizing these objectives.

The recommendations documented in this report represent the wind energy and atmospheric physics research communities' incipient thoughts, and advancement beyond this initial stage will require more detailed documentation and long range planning. Together, these will lay the foundations for a challenging collaborative research agenda of wind resource characterization in support of aggressive wind energy deployment to meet strategic U.S. energy needs.

Detailed Recommendations – Turbine Dynamics

3. Isolated Turbine Inflow Characterization

3.1 Abstract

An accurate representation of the inflow to a wind turbine is critical to several aspects of wind turbine design, deployment, and operation. Chief among the needs is a realistic inflow for designing the wind turbine. Unfortunately, the current ability to predict wind flows for specific sites (e.g. the Great Plains) that are relevant to today's wind turbines are good approximations at best and totally inappropriate at worst. Related to this lack of modeling capability is the lack of information concerning the planetary boundary layer between 100 m and 1 km, particularly those properties of the atmosphere that are most critical to wind turbines. The solution to this lack of understanding and modeling capability is an integrated experimental/observational and computational/theoretical effort. The wind energy industry would benefit from such work in many ways, particularly if it is carried out over the next 5 – 8 years so that the results can have a large impact as the industry rapidly grows.

3.2 Problem or Opportunity

3.2.1 The Need

Current wind turbines suffer premature failures and reduced lifetimes from those predicted during design. Such shortfalls represent uncertainty to prospective investors. Turbine down-time and complete turbine failure lead to a lower return on the investment than predicted. This lowers the confidence of investors and thus increases the cost of raising capital necessary to develop a wind plant.

A key reason for these early failures is our lack of knowledge of the unsteady wind inflow that approaches and then interacts with the turbine. It is known that unsteady blade aerodynamics are the cause of unsteady loads on blades that leads to failure, but these unsteady loads can not be predicted if unsteady inflow is not well characterized. This example shows how wind inflow is inexorably linked to blade loads and thus to every system in the turbine. For example, control of the turbine might be used to mitigate harmful loads, but without the ability to simulate these loads accurately, how can effective control strategies be developed? From this example, it is clear that an accurate wind inflow is absolutely necessary to improvement of wind turbines as it is the root of all other issues considered. Improvement in our understanding and modeling of turbine wind inflow would have an immediate beneficial impact in several areas of turbine design.

Aside from the turbine itself, there are other issues why accurate wind inflow simulations are needed. When siting wind plants, the developer needs a tool that can accurately estimate the local wind resource to optimize turbine placement. When operating a wind plant, accurate forecasts of the wind resource facilitate the integration of wind energy into the electrical grid and thereby making the power more valuable.

3.2.2 The Opportunities

Although a clear need for better wind inflow models has been evident for a long time, this is not an easy need to address. The complexity of the near-surface winds (those at altitudes less than 1 km above the ground) and wide range of scales associated with the wind flow, from mm to km, makes simulation of these flows challenging. Traditional mesoscale models developed for weather forecasting were not designed to predict wind with the level of detail required for wind turbine application. A large gap in our knowledge of winds between 100 m and 1 km exists. Current large utility-scale turbines reach above 100 m, and wind structure that interacts with the turbine often descends from well above the 100 m level. Large eddy simulations (LES) embedded within a mesoscale model may aid in understanding this region of the planetary boundary layer. Such approaches are being used for other applications (e.g. biological and chemical dispersion), but challenges still exist. For instance, how are the boundaries where the embedded LES starts treated? What data can be used to validate the simulations?

Our lack of knowledge of the wind inflow resource is directly related to the lack of field experiments relevant to wind turbines. Although many field studies have been carried out and long-term wind data from airports exist, they are at the wrong heights and do not acquire and archive the type of data needed for characterizing the inflow. Field campaigns with a focus on wind field properties important to wind turbines are needed.

3.3 Research Approach

To develop relevant unsteady wind inflow modeling capability, an integrated approach using both simulation and theory, as well as experiment and field observation, is logical. Initial simulations would provide guidance on how to perform effective field experiments. Field experiments could then be used to validate and improve existing simulation capabilities as well as to assist in developing new simulation strategies. In addition to performing field studies, efforts toward developing instrumentation that can provide required atmospheric data should also be addressed. In the following sections, suggested experiments and computational/theoretical needed to move the field ahead are proposed.

3.4 Needs from Computation/Theory

In this integrated experimental/computational effort, ***the first modeling efforts should be oriented toward identifying locations for field campaigns and investigating how to distribute various instrumentation systems to optimize the data obtained.*** Existing simulation methods can be used for this effort.

Although many simulation methodologies exist, they are not always representative of the true inflow. Data from field campaigns should be used to evaluate existing models and to identify their shortcomings. Out of this effort, ***a new hierarchy of simulation methodologies should be developed***. Highly complex models that capture many of the essential flow physics should be developed in parallel with lower-order models that capture key details of flow at significantly lower computational cost.

Development of complex physical models should be undertaken to provide a better understanding of near-surface winds. Results from such models would aid in our understanding of the processes occurring in the planetary boundary layer as well as guide development of lower-order models. These models could also be valuable in identifying those types of disturbances to which turbines are most sensitive. For instance, wind inflow from such a model could be used with a turbine design code to identify those structures that are driving fatigue. One approach commonly used for developing such wind inflows is LES of the planetary boundary layer. Some of these models are run stand-alone with periodic boundary conditions. Pressure gradients typical of the area (which can be determined from mesoscale models) are used to drive the flow. Such a simulation is shown in **Figure 1** where a Kelvin-Helmholtz billow is simulated in a flow typical of a low-level jet. Another approach is to embed LES simulations within a larger mesoscale model. For both approaches, the LES resolution required for wind turbine inflow must be considered (is 1 m enough?), as well as identifying those sub-grid scale models that are computationally efficient yet provide realistic results. For the embedded LES approach, how are the boundaries of the LES simulations initialized using the mesoscale model results?

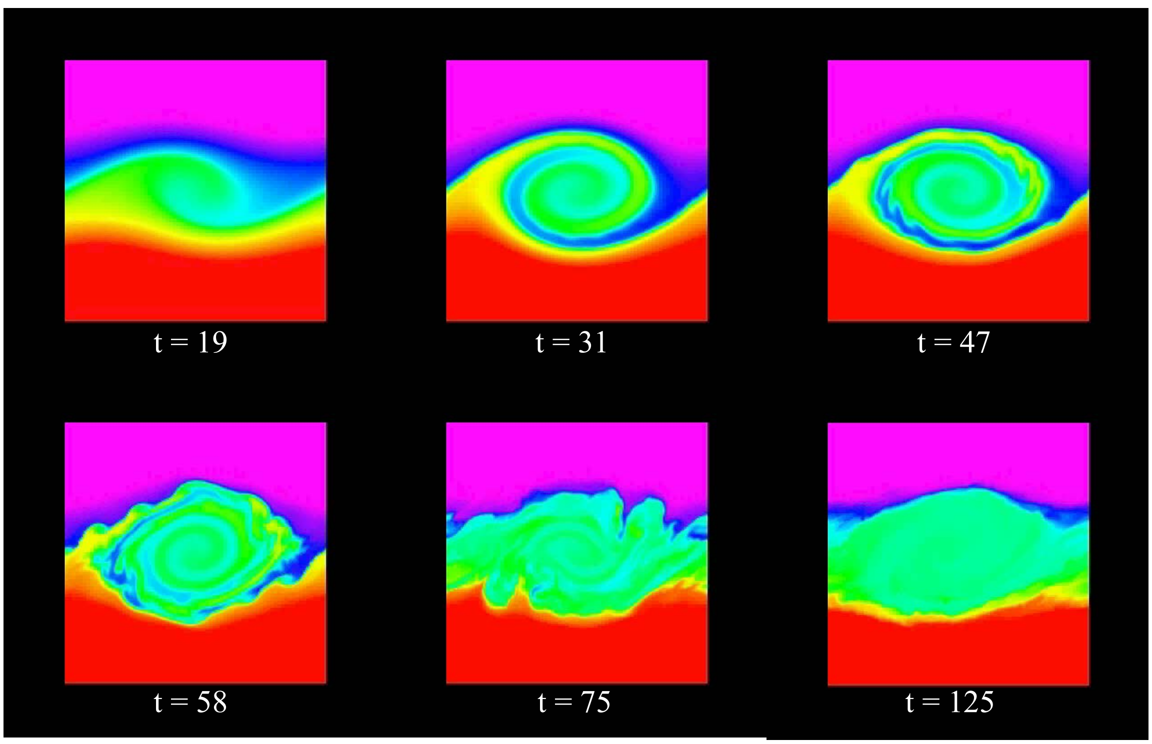

Figure 1 - Time evolution of 2-D slices of temperature from a 3-D large-eddy simulation (LES) of a Kelvin-Helmoltz billow (purple: hot, red: cold) generated by the National Center for Atmospheric Research's LES code (see Kelley et al. (2004) for details). Times are made non-dimensional by a characteristic time scale defined by the height of the billow and the free-stream velocity defining the magnitude of the velocity shear.

In addition to using wind inflow simulations to better understand the environment in which these wind turbines operate, it is also often necessary to run a set of parametric inflows for design purposes or to develop models that can run over very long times. As a result, in tandem with the more complex models, ***reduced order models that are computationally efficient yet capture the***

important essential physics should be developed. Development of methods that complement the existing stochastic spectral approaches should be undertaken. In the development of these methods, a balance between the physics captured and the computational efficiency must be struck. Field test data and the results from the more complex simulation approaches can be used to aid in selecting those physics that are essential to keep. Tying these approaches to mesoscale models capable of capturing larger scale effects of weather and terrain would be beneficial. Such models would obviously be valuable for wind plant siting and wind forecasting.

3.5 Needs from Observations/Experiments

Wind resource field observations provide two valuable roles: they provide validation cases for models of wind inflow, and they provide insight about winds in the 100 m to 1 km gap where our knowledge of wind field dynamics is not complete. To develop an understanding of the wind resource in this vertical region, ***a set of field campaigns at several "typical" sites is recommended. These sites could include, for example, one in the Great Plains, one in a Mountain Valley, one in an Eastern Forest, and one on the Great Lakes.*** These field campaigns would build upon previous successful wind resource characterization campaigns with turbines (e.g. the Long Term Inflow and Structural Testing (LIST) experiment shown in Figure 2) and without turbines (e.g. the low-level jet field test shown in Figure 3). Future experiments will ensure that data with time and space resolution sufficient to characterize relevant unsteadiness/turbulence in the wind turbine inflow environment are obtained. Single towers, even so-called tall towers, are not sufficient for these types of tests. Instead, tests should be driven by perceived needs. For example, horizontal and vertical correlations, spatial information to 30 m, and identification of the inflow unsteadiness/turbulence that significantly impacts the turbine are all important to wind resource characterization. Although sufficient spatial and temporal resolution is needed, a sufficiently long test duration is also necessary to capture diurnal and seasonal variations as well to characterize the nature of extreme events present at that location. At all sites, the vertical and directional shear as well as the effects of atmospheric stability should be characterized. In addition, features particular to the given location, such as low-level jets in the Great Plains (Figure 4) and mountain waves in the lee of the Rockies, should be investigated. Although intensive measurements will be of limited duration, less involved long-term measurements should be continued. In this way, the long-term characteristics of the site would be developed and follow on investigations with new instrumentation (as it is developed) could be carried out.

Although the pressing need for such measurements will necessitate the use of available instrumentation such as arrays of towers, SOnic Detection And Ranging (SODAR), and LIght Detection And Ranging (LIDAR), development of instrumentation for measurements needed for wind resource characterization should be pursued. Although time-resolved measurements over an entire wind inflow plane would be the ultimate goal, intermediate steps such as multiple point scanning systems capable of reaching to 300 m would be beneficial. To go along with such measurements, techniques to estimate the wind-inflow dynamics from limited measurements should be developed. As instrumentation and analysis methods are developed, field tests at the same sites listed above (Great Plains and Rockies) should be carried out to further improve our understanding of the near-surface wind field. A related instrumentation effort is development of an inexpensive system for monitoring wind from the wind turbine for anticipating the wind inflow. Such capability would permit identification of the inflow needed to implement control to reduce turbine loading and increase efficiency.

Figure 2 - NREL Long-Term Inflow and Structural Testing (LIST) Program (see Kelley et al. (2002) for details). Inflow turbulence measurement array looking downwind towards the NWTC 600-kW CART turbine. Photo by Warren Gretz (NREL).

(a) (b)

Figure 3 - Low-level jet field test near Lamar, CO (See Kelley et al. (2004) for details) : (a) GE Wind 120-meter meteorology tower, and (b) acoustic wind profiler (SODAR) flat-plate, 64-element phased array antenna base. Photos by Warren Gretz (NREL).

3.6 Potential Wind Energy Impact

The impact of the work proposed here will be felt quickly as our understanding and ability to model the unsteady turbine inflow improve. Understanding what fatigues wind turbines will enable more reliable turbine designs. Likewise, better inflow models will allow for the development of turbine control strategies that can minimize unfavorable loading and can increase efficiency. As the ability to simulate winds at specific sites improves, improved siting of wind plants and enhanced power production prediction will be possible. Involvement of industry in work suggested here is critical so they can benefit from some results immediately and plan for using the new tools as they become available.

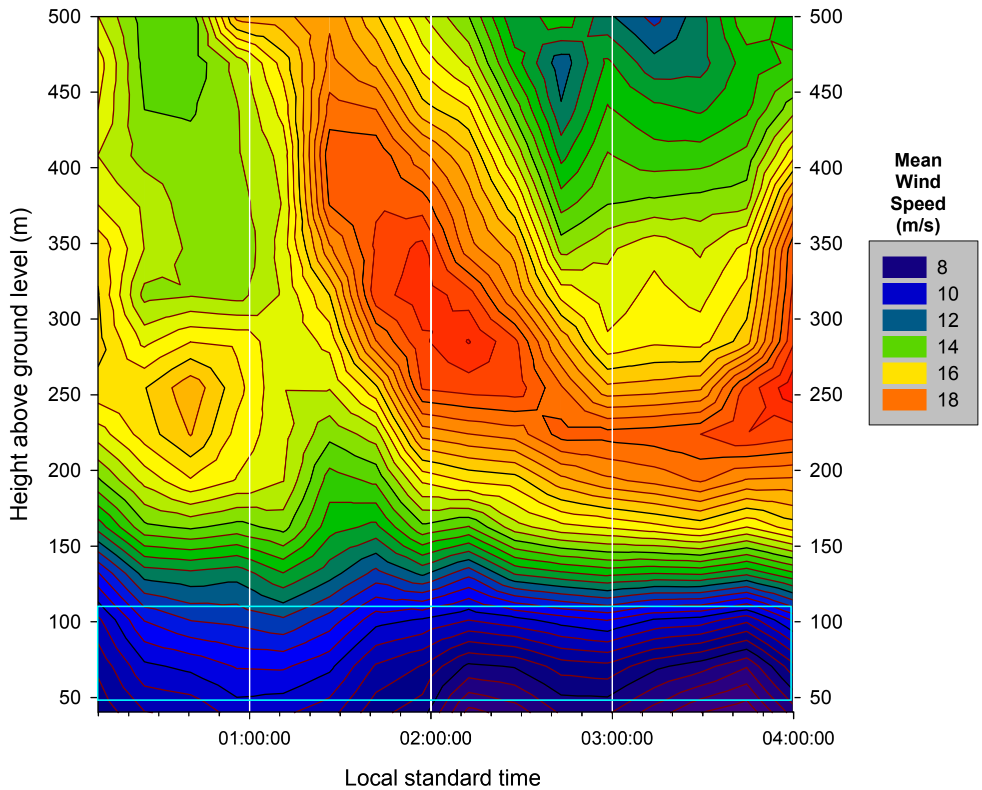

Figure 4 - The evolution of well-formed low-level jet structure observed during the early morning hours of June 17, 2002, on the high plains south of Lamar, Colorado. The contours of 10-minute mean wind speeds with height show an initial jet forming about 00:30 h at a height of about 250 m, but then replaced by a higher jet forming between 450 and 500 m at 01:30 h. The latter jet then increases in speed and descends back to 250 m as the night goes on. This jet does not break down into turbulence, but induces very high values of vertical wind shear in the area outlined in cyan representing the height range occupied by a GE 1.5-MW wind turbine rotor. See Kelly et al. (2004) for details.

3.7 Key Events and Approximate Timing

The earlier this effort starts and the more intensive the effort, the sooner it can have an impact on the wind energy penetration into the market. Better turbines, improved siting, and more accurate forecasting that will be possible with the models developed here will all improve the deployed performance of wind turbines. With reduced uncertainty about the turbine's operation, investor confidence will rise, reducing the financing cost, and thus, the overall cost of wind energy. The federal government has indicated that up to 20% of our electricity can be supplied by wind (Advanced Energy Initiative, February 2006). For this to occur in a timely fashion, it is important that work suggested here is undertaken and completed within the next 5 – 8 years so that it can have an impact on the large number of wind turbines to be installed in the 2015 to 2030 time frame.

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4. Ingestion of Wake from Upwind Turbines

4.1 Abstract

Wind turbine blade and wake flow fields are energetic, complex, and challenging to characterize, even in isolation from each other. Moreover, when a wind turbine rotor ingests the wake produced by an upwind turbine, complexity proliferates as powerful physical mechanisms restrict energy capture and amplify destructive fatigue loads. Though these adverse effects strongly impede turbine operation and substantially increase cost of energy, present capabilities for measuring or predicting them remain limited. Development of accurate, reliable methods for characterizing turbine operation in the presence of wake ingestion would help formulate effective solutions to problems that currently hinder wind turbine operation and wind plant productivity.

4.2 Problem or Opportunity

During routine operation, a wind turbine rotor produces a wake consisting of vorticity shed from the rotating blades. The principal structures present in the wake are cohesive helical vortices trailed from the blade root and tip, and helicoidal vorticity sheets simultaneously emitted from the blade's central portion. Because of rotor energy extraction, this wake incurs a momentum deficit with respect to the undisturbed flow outside the wake. Wake structure becomes even more complicated when vertical or horizontal shears are added to the inflow velocity profile, or the rotor is yawed with respect to the wind inflow direction. Under these conditions, the blades undergo dynamic stall, which disrupts the circumferential uniformity of the tip vortex, and injects large, energetic vortices into the previously undisturbed helicoidal vorticity sheets. Though diffusion, vortex instabilities, and similar phenomena tend to dissipate the wake, it persists downwind of the rotor for several disc diameters.

In wind plant arrays, turbine wakes can be ingested by downstream turbine rotors, depending on wind inflow conditions. When this occurs, turbine operation and cost of energy are adversely impacted in two general respects. First, because the downwind rotor is at least partially immersed in the low momentum wake trailed by the upwind rotor, less energy is available for extraction, thereby reducing energy capture by the downwind turbine. Second, as the downwind rotor blades intersect the spatially complex vorticity field generated by the upwind rotor, downwind rotor aerodynamic loads suffer large, rapid oscillations, which prematurely exhaust turbine structural life. It is likely that these two phenomena, as well as other unidentified wake ingestion interactions play prominent roles in wind plant underperformance and premature failure of blades and gearboxes. However, current understanding of turbine wakes and ingestion events remains incomplete. This precludes accurate modeling of these effects and reliable prediction of adverse impacts on wind plant operation and turbine reliability. While initial concentration will focus on the two-turbine circumstance, longer term approaches ultimately will need to address multiple turbine rows in modern wind plants.

4.3 Research Approach

Fundamentally, the turbine wake ingestion problem consists of interaction between a wake generated by an upwind turbine and the rotor blades of a downwind turbine. Thus, accurate, reliable prediction of wake ingestion and resultant effects will require detailed characterization and understanding of both blade and wake aerodynamics. However, spatial scales that govern these phenomena range from microns up to hundreds of meters, and involve a correspondingly broad range of temporal scales. This scale range requires developing and maturing approaches capable of accurately, reliably, and efficiently characterizing these expansive scale ranges. Specifically, there exists a need for complementary prediction and measurement capabilities, which can be used in mutually supportive fashion to furnish information and formulate solutions to problems precipitated by turbine wake ingestion.

4.3.1 Computational Prediction

Dynamic mesh adaptation can help increase predictive accuracy and bound computational workload by increasing mesh density only where higher spatial resolution is deemed necessary, as determined with reference to the evolving computational solution (Duque et al.). Anisotropic adaptation to match grid element shape to the local physical length scales offers substantial reduction in computational effort (Sahni et al.). Although effective in limiting the total number of mesh points, grid adaptation can lead to load balancing difficulties on parallel architectures, and can carry significant implications with respect to solver algorithms. Also requiring consideration are grid condition in the domain interior, interconnection of adjacent grid blocks, and imposition of grid boundaries at physical surfaces, all of which can impair solution accuracy.

Adaptation of the solver algorithm also holds potential for improving accuracy and managing computational workload. Across the hierarchy of solver algorithms, direct numerical simulation (DNS), large eddy simulation (LES), detached eddy simulation (DES), and Reynolds averaged Navier-Stokes (RANS) employ differing degrees of phenomenological approximation and offer varying levels of accuracy. DNS and LES place greater reliance on first principles computation to gain improved accuracy, but carry significantly higher computational costs. Alternatively, DES and RANS reduce computational costs, but do so by placing greater reliance on nonphysical models and allowing associated reductions in fidelity.

Wind turbine blade and wake size coupled with DNS and LES computational costs preclude uniform application throughout the computational domain, even using petascale architectures (Spalart 1997). However, these models could be selectively applied as the flow field solution evolves, in separation regions, shear layers, vortices, and other regions of strong nonlinearity, to resolve these structures and mitigate numerical diffusion. In the remainder of the flow field, less computationally expensive methods could be applied. Achieving this goal also will require that the “switch over” between models and corresponding flow field sub-regions (Figure 5) be rigorously understood and correctly addressed at the algorithmic

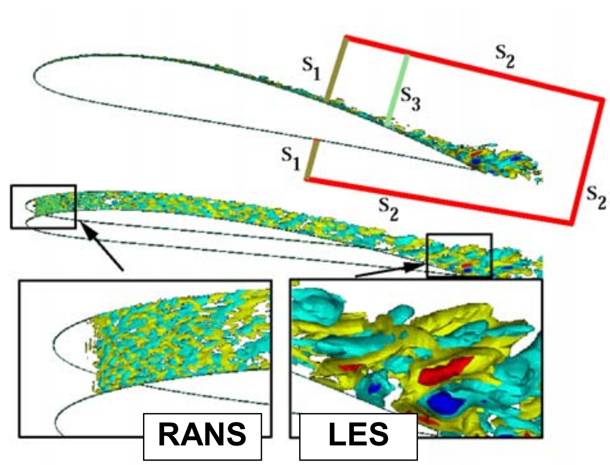

Figure 5: Hybrid models apply high fidelity models only where required, simple models elsewhere, and manage “switch over” in between (S_3 interior data augments S_1 model boundary data).

level (Araya 2006). This will be particularly important for wind turbines, since inflow conditions change rapidly, dictating similarly rapid alterations in flow field structure.

4.3.2 Field Measurements

Modern utility-class wind turbine rotor diameters currently exceed 100 meters, with blade tips that extend as high as 150 meters above ground level. Future conceptual designs have rotors of substantially greater diameter, and blades will reach 200 to 300 meters into the atmospheric boundary layer. Turbine rotor wakes of interest in the future will be 100 to 200 meters in diameter, several hundreds of meters long, and 100 to 200 meters above the ground. The domain of interest is expansive, and the spatial scales of interest extend from wake dimensions (100's of meters) down to blade boundary layer scales (microns). The spectrum of temporal scales are similarly broad.

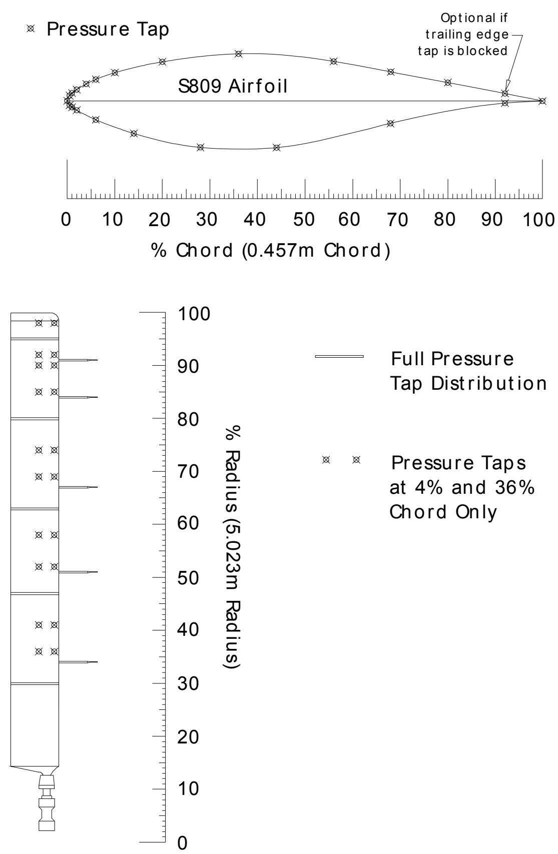

Figure 6: Schematic of NREL Phase V Unsteady Aerodynamics Experiment turbine blade surface pressure measurement locations.

Flow field characterization on blade surfaces of turbines operating in the atmosphere currently can be carried out with high accuracy and reliability, although sensor physical size and cost constraints tend to limit spatial resolution. Surface pressure measurement using commercially available transducer technology has matured significantly, and associated uncertainties have been driven well below desired levels. Figure 6 shows a schematic drawing of the blade surface pressure measurement locations for the Phase V Unsteady Aerodynamics Experiment turbine (Hand et al., 2001). Characterization of the blade boundarylayer turbulence state during field operation using commercially available microphone technology has been proposed, but has not yet been implemented. Next generation MEMS based pressure transducers and microphones could reduce physical size and cost, thus relieving current limitations on spatial resolution. Flow field characterization above the blade surface, whether quantitative point measurements or qualitative flow visualization, would be time and resource intensive, and used in a precisely targeted fashion.

Characterization of turbine wakes using tall (100 to 200 meter) towers enables a variety of high performance instruments to be precisely located on a long term basis. Although extremely costly, this significantly reduces spatial uncertainty in the measurement, and provides some flexibility concerning instrumentation choice. However, since the tower is fixed, virtually no flexibility exists for selectively locating instrumentation in the wake. Moreover, under some inflow conditions, the wake will miss the tower and thus render wake measurement impossible. Alternatively, remote sensing approaches, like SODAR and LIDAR (Harris, et al.), would enable flexible movement of the measurement volume through the turbine inflow or wake, as shown in Figure 7. At present, both types of instruments readily measure along line of sight. Three-dimensional measurements in a compact measurement volume, with the ability to rapidly scan the measurement volume through the wake/inflow domain, would entail significant technical challenges, but would provide a crucial capability for detailed flow field characterization.

Figure 7: Wind turbine inflow measurements using hub-mounted LIDAR .

4.3.3 Data exploitation

Because of the expansive domain of interest, broad spatial and temporal scale range, diverse data (computational and experimental), and the range of applicable turbine operating conditions, data sets will be overwhelmingly large. For example, a computational simulation using a 10^9 point mesh and run for 10^6 time steps will yield a petascale data set. Field experiments will use substantially fewer measurement points, but will be run for much longer times to capture inflow conditions representative of the statistical range, and also will yield staggeringly large data sets. Because of the nonlinear, time dependent nature of wind turbine flow fields, crucial flow structures and events may be spatially and/or temporally compressed, and thus not readily detected. To efficiently interrogate these extremely large computational and experimental datasets in a consistent and mutually supportive manner, reliably identify key flow structures and events, and arrive at thorough comprehension of key machine responses, automated data mining methodologies will be required.

4.4 Needs from Computation/Theory

- Dynamic mesh adaptation to help resolve/preserve key flow structures/processes and bound computational workload
- Adaptative solver algorithms that span the DNS/LES/DES/RANS hierarchy to improve physical fidelity and manage computational workload
- Algorithms to interrogate extremely large computational and experimental data sets, in a way that exploits synergies between predicted and measured data.

4.5 Needs from Observations/Experiments

- Application of state-of-the-art blade flow field measurement instrumentation and targeted transition to next generation MEMS-based technologies
- Development and application of remote sensing technologies for wake and inflow characterization, particularly 3-D scanning LIDAR
- Selective use of instrumented tall towers to acquire specific data in advantageous conditions or environments.

4.6 Potential Wind Energy Impact

Detailed physical understanding and accurate, reliable prediction of wake ingestion by wind turbines will confer several benefits on wind energy machine technology and wind plant operations. Initially, understanding and prediction will focus on the fundamental two-turbine interaction, but ultimately will advance to encompass interactions between multiple turbine rows like those in modern wind plants. Specific impacts will favorably impact wind cost of energy through turbine capital cost and lifetime, operations and maintenance costs, replacement costs, finance costs, and energy capture. Specific impacts include those listed below.

- More reliable predictions of wind plant energy capture performance
- More credible forecasts of turbine lifetime and component failure
- Operating practices that reduce upwind wake shedding and mitigate downwind wake effects
- Turbines designed and built to better tolerate wake ingestion
- Wind plant optimization that intelligently balances land area usage and turbine effectiveness.

4.7 Key Events and Approximate Timing

All times below are referenced to project funding initiation at Year 0.

- Years 1 – 3: Develop blade and wake flow initial measurement capability
- Years 1 – 3: Develop initial predictive methodologies for two-turbine interaction
- Year 4: Acquire initial blade and wake flow measurements
- Year 4: Validate initial predictive methodologies for two-turbine interaction
- Year 5: Acquire additional measurements in response to predictions
- Year 5: Revise predictive methodologies in response to validations.

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5. Extreme and Anomalous Inflow Events

5.1 Abstract

Wind turbines are subject to extreme and anomalous wind-inflow events that affect their operation, loading, and durability. Improved foreknowledge of such events in the design stage will help wind turbine designers better develop configurations and control methodologies that mitigate the impact from the events, reducing ultimate loads and fatigue damage. The research approach calls for observations and computations to better characterize important inflow conditions, incorporation of the improved inflow conditions into the design process through modifications to the wind turbine design standard, and sensor and controls development for real-time detection and mitigation of inflow events. This research will decrease a wind turbine's design overhead and its associated costs, make turbine design refinement easier, and reduce the overall cost of wind energy.

5.2 Problem or Opportunity

Wind turbines are subject to wind-inflow conditions that affect their operation, loading, and durability. Of particular concern are extreme wind conditions that exceed the inflow prescriptions used as a basis for the wind turbine design and/or anomalous inflow events that were not accounted for in the design. Extreme and anomalous wind-inflow events are those that have spatial-temporal characteristics which make them potentially damaging to a wind turbine. Examples include wind gusts, rapid changes in the wind direction, shears of wind speed and wind direction across the rotor, spatial coherence in wind components, and combinations of these conditions.

The characterization of extreme and anomalous inflow events is complicated by the reality that it is not the magnitude of the inflow condition that is important, but rather its impact on the wind turbine. The impact of an inflow event on a wind turbine depends on the turbine's configuration and operational state (i.e., power production, start-up events, shut-down events, parked and/or idling, and fault conditions). Extreme and anomalous inflow events are likely to generate the highest (i.e., ultimate) loads experienced by a turbine, but may also contribute to its fatigue damage depending on the frequency of the events at any particular site and the extent to which a turbine component's fatigue resistance is influenced by the largest amplitude cycles.

The International Electrotechnical Commission (IEC) 61400–1 design standard [1] specifies the design requirements for utility-scale land-based wind turbines. This design standard requires that an integrated loads analysis be carried out. Loads analysis involves verifying the structural integrity of a wind turbine by running a series of design load cases (DLCs) using comprehensive aero-servo-elastic design tools to determine the ultimate and fatigue loads expected over the lifetime of the machine. The loads (i.e., forces and moments) are examined within the primary members of the wind turbine, including the blades, drivetrain, nacelle, and tower. The required DLCs cover essential design-driving situations by pairing up the wind turbine's operational states with appropriate normal and extreme external conditions.

Table 1: Description of the IEC Idealized Wind Models.

Abbr.	Definition	Description
ECD	Extreme Coherent Gust with Direction Change	This deterministic wind model consists of an unsheared gust superimposed on a NWP. The gust rises to 15 m/s over a 10-s period. Occurring concurrently, the wind direction changes inversely proportional to the given hub-height wind speed. Both positive and negative direction changes are considered.
EDC	Extreme Direction Change	This deterministic wind model consists of a transient direction change to the NWP. Over a 6-s transient, the wind direction changes depending on the wind class and inversely proportional to the given hub-height wind speed. Both positive and negative direction changes are considered.
EOG	Extreme Operating Gust	This deterministic wind model consists of an unsheared gust superimposed on a NWP. Over a 10.5-s transient, the gust first dips, rises to a maximum, and then dips again before disappearing. Its magnitude depends on the wind class and increases with the given hub-height wind speed.
ETM	Extreme Turbulence Model	This model is similar to the NTM but consists of full-field 3-component stochastic winds with a higher turbulence standard deviation depending on the wind class and increasing with the given hub-height wind speed. Like the NTM, the full-field turbulence is superimposed on a NWP.
EWM	Steady and Turbulent Extreme Wind Models	Models consist both of high, steady, and turbulent wind speeds dependent on the wind class. The turbulent model consists of full-field 3-component stochastic winds. The steady winds and full-field turbulence are superimposed on a wind profile with a vertical power-law shear exponent of 0.11.
EWS	Extreme Wind Shear	This deterministic wind model consists of a linear speed shear superimposed on a NWP. Over a 12-s transient, the shear rises to a maximum, and then decreases again before disappearing. Its magnitude depends on the turbulence category and increases with the given hub-height wind speed. Positive and negative, vertical and horizontal, shears are considered independently.
NTM	Normal Turbulence Model	This model consists of full-field 3-component stochastic winds with a turbulence standard deviation given by the 90% quantile depending on the wind turbine turbulence category and increasing with the given hub-height wind speed. The full-field turbulence is superimposed on a NWP.
NWP	Normal Wind Profile	Wind speed profile with a vertical power-law shear exponent of 0.2.

The design standard uses an assortment of idealized wind models (including normal and extreme, and turbulent and deterministic models) as the basis for the turbine design. The model parameters are quantified through the specification of a wind speed class and turbulence category. The wind models are described in Table 1 for readers who are unfamiliar with the IEC terminology. The extreme wind models were formulated for the design standard based on a limited set of observations that were made during the early years of modern wind turbine development and known to be damaging to turbines of that era.

The developers of the design standard understood that the design basis and loads analysis calculations are imperfect, so the design standard requires that partial safety factors be applied to the loads (among other factors). This introduces a design overhead that adds cost to the wind turbine and makes design refinement difficult.

Wind models formulated in the design standard—and the overall design process in general—could be improved if more spatially-detailed and time-accurate representations of extreme and anomalous inflow events were available. Important inflow events could be characterized using a combination of observations and computations. Improved foreknowledge of extreme and anomalous wind-inflow events in the design stage will help wind turbine designers develop better configurations and components that mitigate the impact from the events, reducing ultimate loads and fatigue damage. Moreover, if impinging conditions could be detected in real time, information about the conditions could be passed to the wind turbine's safety and protection system so that the turbine's control system could take action before damage occurs. Dramatic loads reductions could be obtained through such feed-forward control strategies.

5.3 Research Approach

In light of these problems and opportunities, a multifaceted research project will be required to characterize extreme and anomalous inflow events and to modify the design process and design features of wind turbines to mitigate the impact of the events.

The first research task must be to obtain more spatially-detailed and time-accurate representations of extreme and anomalous inflow events. This will require a combination of observations and computations.

Experimental observations are needed to establish a reference of physically measured inflow conditions. Although individual anemometers are useful in measuring the annual distributions of wind speed and the magnitude of extreme wind speed gusts, individual anemometers are not useful for measuring the spatial-variability of the inflow. As the spatial-temporal characteristics are also attributes that make them potentially damaging to a wind turbine, more detailed observations are required. Capturing the needed spatial-temporal characteristics of the inflow will require the use of arrays of sonic anemometers, SODAR instruments, and/or scanning LIDAR instruments.

Observations should be taken from a variety of locations to reflect possible site-to-site variability (e.g., complex terrain, Great Plains, near shore, or offshore sites) in the inflow characteristics. Extreme and anomalous inflow events by their nature may not occur frequently at all sites, so it is also important to make observations from a variety of locations simultaneously. Furthermore, it will be beneficial to make some of the measurements near—and correlated with—the response measurements of one or more turbines in wind plants. This correlation will help identify the inflow characteristics that most adversely affect the turbines. Not all inflow measurement locations must be collocated with wind plants, however, as inflow characteristics that are benign to one type of wind turbine may be important to another type, and vice versa.

Such a large-scale observation campaign can be established most easily by spreading the work across multiple research organizations around the United States. A publicly available and editable database should be established to share information about phenomena that have been measured. This database should first be populated with historical records on measured extreme and anomalous inflow events, such as the data used to formulate the extreme wind models in the IEC wind turbine design standard.

The amount of information collected about the spatial-temporal characteristics of extreme and anomalous inflow events in observations is nevertheless limited. Consequently, the observations must be supplemented by mesoscale and microscale atmospheric computations. Mesoscale atmospheric models should be developed and run to help quantify variations in the inflow event characteristics for scales in the range of 1 to 1,000 km—that is, between the synoptic and microscopic scales. These scales are important for quantifying flows involving storm convection, complex terrains, sea breezes, and the progression of storms across multiple wind plants in any particular region. Microscale atmospheric models, such as LES models, should be developed and run to help quantify the detailed flow physics for scales less than 1 km—that is, inflow local to a single wind plant or wind turbine. Where even more detail is required in the LES's sub-grid scale, DNS models must be applied.

The outputs from the microscale atmospheric models should then be used as inputs to computational aero-servo-elastic models of wind turbines to help isolate the inflow phenomena that are important to the turbine response. Neil Kelley and Bonnie Jonkman of NREL have initiated research in this area [2]. Currently, Blade-Element / Momentum (BEM) and Generalized Dynamic-Wake (GDW) are the rotor aerodynamic theories used in routine design, but it may be necessary to apply higher fidelity theories such as vortex (free) wake methods or Computational Fluid Dynamics (CFD) because extreme and anomalous events are likely to involve high nacelle-yaw errors and transient conditions that are not modeled well by the simpler theories.

Once the extreme and anomalous wind-inflow events are better characterized, the next research task should be to update the IEC design standard with modified parameters in the extreme wind models and/or with new models and load cases. Updating the design standard is important because it dictates the design of wind turbines. The form, magnitude, and duration of the wind gusts, direction changes, and shears prescribed in the deterministic ECD, EDC, EOG, and EWS wind models (see Table 1) should be updated to better represent the observations and computations obtained in the first research task. New inflow models should be developed that better capture the boundary layer flow physics of other inflow events, such as wind direction shears and coherent turbulent structures brought about by the presence of low-level jets. When such conditions interact adversely with the various operational states of a wind turbine, new load cases should be added to the design standard. The design standard should also give guidance on how the model parameters vary from site to site. Because improvements to the design basis translate directly into reduced uncertainty in loads analysis, improvements to the design basis should also be followed by a reduction in the partial safety factor for loads.

Once the extreme and anomalous wind-inflow events are better characterized, it may also be possible, with further research, to develop methods that can identify inflow conditions in real time. The final research task, then, is to develop methods for detecting specific inflow conditions in real time and to devise feed-forward control strategies that use the real time information to take action in a wind turbine before damage occurs. Perhaps the simplest method of detection would be to establish routine interaction between wind plant operators and meteorologists; meteorologists routinely track storms and could provide wind plant operators with important information regarding the possibility that specific atmospheric phenomena may occur. More useful, though, would be the development of advanced—but inexpensive—sensors such as LIDAR instruments, which could be placed within wind plants or on individual wind turbines to identify specific inflow conditions moments before they interact with a turbine. With the right information passed to the wind turbine's safety and protection system, feed-forward control strategies could be developed to take preemptive measures. For example, the blade-pitch angles could be preemptively feathered collectively or individually to mitigate the potential loading brought about by drastic wind gusts or speed shears, respectively. Other more advanced control strategies that use a combination of blade-pitch, nacelle-yaw, generator-torque, and other control actuations could also be devised to minimize the potential damage caused by extreme and anomalous events.

5.4 Needs from Computation/Theory

To summarize the research approach with respect to computational needs, computations are needed to fill in the data gaps regarding the spatial-temporal characteristics of extreme and anomalous inflow events that will be missing from the observations. Mesoscale and microscale (i.e., LES and DNS) atmospheric models need to be developed to characterize the detailed flow physics for conditions in the regional (i.e., 1 to 1,000 km) and local (i.e., 1 km and less) scales, respectively. The outputs to these models then need to be used to drive aero-servo-elastic models of wind turbines to determine their affect on turbine response and to develop lower-order models of specific inflow conditions that are suitable for use within the IEC wind turbine design standard. Vortex wake methods or CFD may be needed to model the potentially complex interaction between the inflow structures and the turbine response.

5.5 Needs from Observations/Experiments

To summarize the research approach with respect to observational needs, experimental observations are needed to establish a reference of physically measured inflow conditions. Observations need to capture the spatial-temporal characteristics of the inflow and so should involve measurements using arrays of sonic anemometers, SODAR and/or LIDAR. The observations also need to be taken from a variety of locations simultaneously, with some of the measurement locations correlated with response measurements taken from operational wind turbines. The variety of measurement locations is necessary to capture conditions that do not occur frequently, to reflect the possible site-to-site variable of the inflow conditions, and to identify conditions that most adversely impact modern wind turbines. Information gathered from the observations, as well as historical wind measurements, should be shared in a public database. Advanced observational sensors also need to be developed to identify specific inflow conditions real time for use in wind turbine control.

5.6 Potential Wind Energy Impact

Proper modeling of wind-inflow conditions in the design process will aid wind turbine designers to develop better configurations and components that can effectively withstand the induced loads and to develop control methodologies that can effectively mitigate their impact. Improved knowledge of the site variability of inflow conditions will also allow wind power developers to better evaluate turbine placement and aid in site suitability analysis. This will result in improved operational performance and reliability, lessened uncertainty in the planning of Operations and Maintenance (O&M), reduced ultimate loads, and diminished fatigue damage of wind turbines. The wind turbine loads, in particular, could be drastically reduced by applying feed-forward control strategies. All of these benefits will decrease design overhead and its associated costs, make turbine design refinement easier, and reduce the overall cost of wind energy.

5.7 Key Events and Approximate Timing

Better characterization of important inflow conditions using observations and computations is the first (and ongoing) key research event. This research, by itself, will not likely impact the development of wind energy until the new information is incorporated into the design process through improved inflow models. Incorporating improved inflow models in a modified wind turbine design standard is the second key research event and will directly improve design of the next generation of wind turbines created using the modified design standard. The final key research event is the development of sensors and controls for real-time detection and mitigation of inflow events. This research will have an immediate impact on the reliability and cost of wind turbines.

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Detailed Recommendations – Micrositing and Array Effects

6. Improved Wake Models

6.1 Abstract

The majority of wind plants now comprise large arrays of wind turbines arranged in multiple rows. In addition, many wind arrays (discrete clusters of turbines or wind plants) are located within close proximity (a few miles) potentially leading to array interactions where the downstream clusters experience reduced wind speeds and hence power output. This, together with an increase in the size of wind turbines extending into traditionally under-sampled regions of the atmosphere (between 10 and 200 m) mean that current wind plant design and micro-siting models are being used beyond their intended purpose. Models routinely under-predict power performance likely due to; a misrepresentation of the vertical wind speed and turbulence profile, a lack of understanding of the impact of complex terrain on flow, fundamental errors in modeling of array effects/wind turbine wakes and/or a combination of these effects. A major research effort is needed to produce the next generation of wind plant models which are capable of accurately predicting power output for large wind plants in both complex terrain and offshore.

6.2 Problem or Opportunity

Like most renewable energy technology, wind plants require most investment before and during construction, with maintenance costs being relatively small and fuel costs being zero. Because this initial investment is often obtained from third parties like banks and investment companies, the financing package details can be crucial to successful development. This means that initial modeling of power output over a long-time frame must be highly accurate, since under-production of power will cause financial penalties. However, prediction of power output over a 20- or 30-year time horizon is inherently uncertain.

Once a site has been identified as a highly likely contender for development, a highly specialized monitoring program will be undertaken to quantify the mean wind and turbulence characteristics and the results related to the long-term mean conditions. The process of optimizing power output and minimizing fatigue loads, by optimal design of wind plant layouts, can then be undertaken.

Models describing wind turbine wakes were developed mainly in the 1980's (e.g., Ainslie 1988, Troen & Petersen 1989) when wind turbines were relatively modest in size and wind plants usually contained a modest number of turbines. By necessity, these wake models had to be fairly straightforward, building on relatively few wake measurements and constrained to avoid excessive computational demands. However, for single wakes or small wind plants in fairly straightforward (i.e., homogeneous) environments, these tend to exhibit relative good agreement with the available data in terms of power losses (e.g., Crespo et. al. 1999, Barthelmie et. al. 2006). Note, modeling of turbulence in wakes (Crespo & Hernandez 1996) for load calculations tends to focus on for specific cases (Thomsen & Sørensen 1999) (Frandsen and Thøgersen, 1999) while power loss modeling has to encompass the full range of wind speeds and directions. It was pointed out in 1991 that the model performance for large arrays was unknown (Elliott & Barnard 1990) but few surveys have been published to establish model performance even for onshore arrays (Smith et al,2006). It has recently become clear that when these wake models are applied to large offshore wind plant arrays they exhibit considerably lower skill relative to observations (Mechali et al,2006, Barthelmie et al, 2008). In complex terrain, even mean flow is difficult to model (Ayotte et al, 2001) to the accuracy required to perform effective micrositing and the performance of the wind plant/wake models in complex terrain is limited (Prospathopoulos et al, 2008).

6.3 Research Approach

Recognizing that developing wind plant modeling requires significant investment, the European Union funded a number of projects over the last few years including ENDOW (Barthelmie et al. 2002), POW'WOW and Upwind; all of which have a component on wake model development and evaluation (Barthelmie et al, 2007). The Danish government (Denmark is a major supplier of wind turbines and wind energy expertise) also invested in R&D to allow wind plant developers and researchers to work together to evaluate the disparity between wind plant predicted energy output and production (Frandsen 2005, Frandsen et al, 2007). These projects indicate that wind plant models appear to make reasonable predictions of power losses due to wakes in small wind arrays (less than 3 – 4 rows). However, in large offshore wind plants, a very large discrepancy exists between standard predictions of average power loss due to wakes and those which have been observed, which are at minimum 15% of total average power. In large wind arrays on land and/or in complex terrain, it is postulated that similar discrepancies exist. However, because of the commercial nature of wind energy development, this information is rarely made public for individual wind arrays, and owners are reluctant to share wind array data.
It is generally acknowledged that wind arrays under-produce power compared to their initial predictions. This is a serious concern to developers and puts at risk developments of wind energy in areas where resources are marginal.

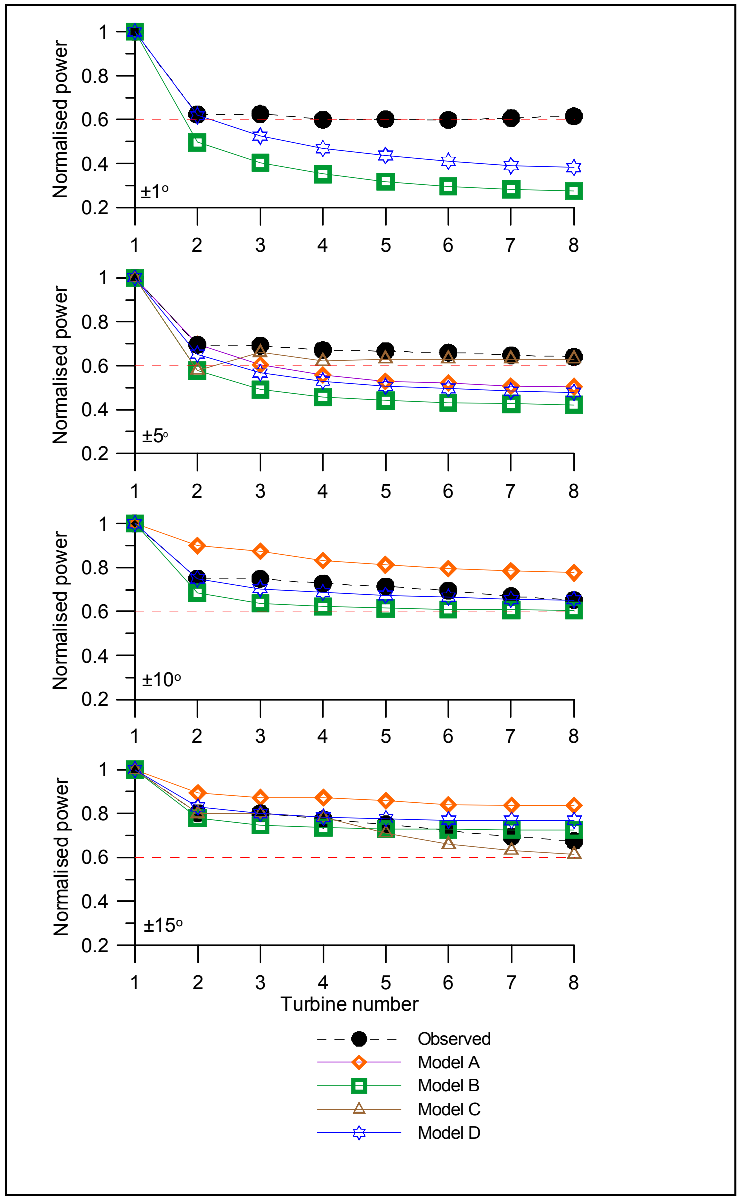

Figure 8. Adapted from (Barthelmie et al. 2008). The observations are from the Horns Rev wind plant taking data from direction 274° (exactly down a row of wind turbines) with different sector widths. The model results shown are from the UPWIND project incorporating both wind plant (parameterized) and CFD models.

6.4 Research Priorities

The scale of wind plant developments is difficult for the public to comprehend. While wind and turbulence could be adequately assessed to about 50 m in the atmosphere, the new turbines with hub-heights of 80 m and rotor diameters of up to 126 m are extending more than 140 m into the atmosphere where there are very few measurements, and it has already been shown that simple logarithmic type profiles used in wind plant models are inadequate (Gryning et al, 2007). Lack of understanding of the basic input parameters to wake/wind plant models over at least 150-m height can therefore be seen as a primary research objective.

The major research priority here is to address the systematic under-prediction of wake losses from large wind plants and hence, the discrepancy between predicted and actual power output that means power production is routinely over-estimated. The most basic approach is to assemble a number of data sets from wind plant operators that can be used first to quantify the extent of the under-prediction, to evaluate the major variables such as wind turbine type, wind speed, turbulence and wind turbine spacing, and to establish whether there are major differences between wind plant behavior in moderate and complex terrain compared with offshore. This research priority can be addressed using data analysis combined with statistical and physical modeling. Although this research sounds straightforward, the complexity of wakes combined with the quantity and quality of datasets available mean that it should not be underestimated.

An additional and parallel approach would be to develop (preferably with a wind energy developer) a long-term wind super-site. This site would have enhanced data collection on the wind turbines, and additional instrumentation upwind and downwind. Additional upwind and downwind instrumentation would include high-resolution (space and time) measurements of the wind and turbulence characteristics upstream, as well as wind and wind plant characteristics downstream.

Once this combined model and data program is underway, priority needs to be given to addressing deficiencies in wake and wind plant modeling in order that uncertainties in micrositing and array effects are reduced. The new generation of models needs to be able to optimize wind plant layouts for large arrays in complex terrain and offshore using newly developed theoretical approaches combined with state-of-the-art modeling techniques, while retaining the current simplicity of input data and use that makes these tools practical for wind energy developers.

In brief, the research plan would:

- Identify wind plant data partners
- Develop methods of protecting proprietary data and enabling industry buy-in
- Collect and analyze wind plant data – ongoing; likely a 1 – 2-year period
- Compare existing models and identify model deficiencies
- Improve model parameterizations and demonstrate improved performance.

6.5 Needs from Computation/Theory

Increased computational resources and improved observational capabilities mean (1) wake modeling is no longer confined to engineering approximations and that CFD modeling of the whole wind plant can be undertaken, and (2) the quality of observations available for both process-level studies and model evaluation is now sufficient to facilitate more meaningful diagnostic analyses and more rigorous model evaluations. This brings a new dimension to wake models in terms of the detailed temporal and spatial variation that can be modeled. There is a gap between analytic solutions that are used in commercially available wind plant models (e.g., WAsP from Risø National Laboratory and WindFarmer from Garrad Hassan) due to ease of use and speed and CFD models. A bridge is needed between these to provide more detailed information for modeling power losses, for better wind plant and turbine design, and (later) for more sophisticated control strategies and load calculations. Challenges remain in terms of model evaluation in operational wind plants because measurements are still not available on a finely spaced mesh over the wind plant, nor (typically) at high time resolution.

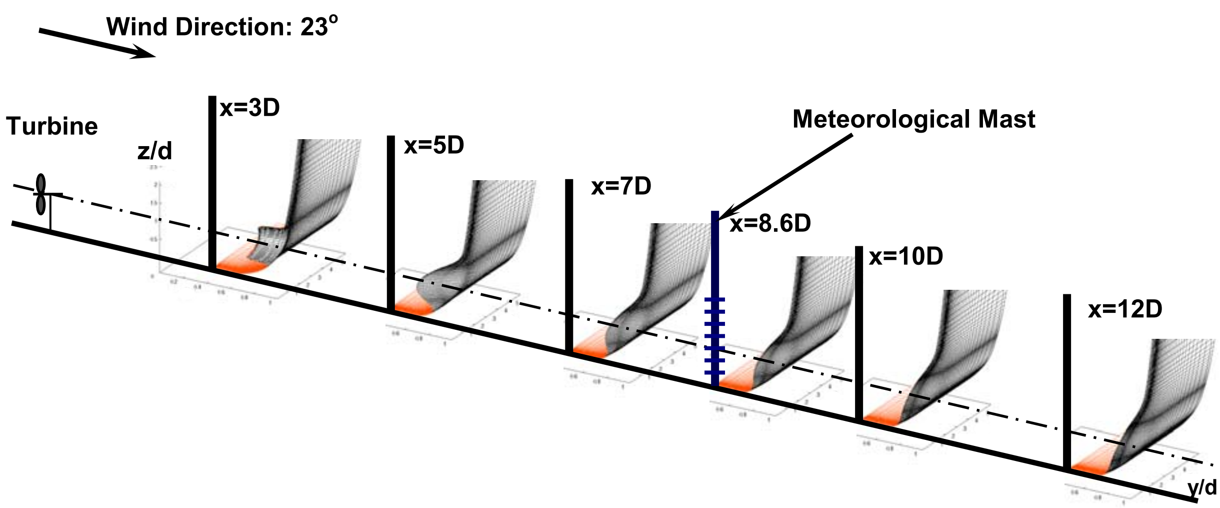

Figure 9. Example of CFD modeling at Vindeby from (Rados et al,, 2002)

A parallel approach is needed to develop theoretical methods to account for behavior of wakes in large wind arrays (expansion, lateral and downwind merging) and interaction between wakes and the overlying boundary-layer (Frandsen et al, 2006). Although these may ultimately prove too complex for routine use (in terms of input parameters and /or computing time), this research is essential if sufficient understanding of these physical process is to be generated to find engineering solutions which can be applied in the wind plant/array models that are currently used by wind energy developers (Schlez et al, 2006).

6.6 Needs from Observations/Experiments

Most wind arrays now have Supervisory Control and Data Acquisition systems that, at a minimum, record power output and a status signal. Unfortunately, this is routinely of poor quality or not stored at high resolution because its long-term utility to the wind array owner does not require this investment. The first task must be to establish good practices that enable the routine data output of many wind arrays to be utilized for fundamental data analysis. Ideally, more signals would be recorded including, for example, yaw angle and wind speed of the nacelle anemometer. For power output analysis, it is likely that 10-minute averages and standard deviations are sufficient, but it might be prudent at this point to also consider what would be required for fatigue and extreme load modeling and institute one set of guidelines to be established. In addition to these data, data from supporting metrology masts in and around the site are useful.

Beyond this, it is possible to elaborate on the design of a wind ‘super-site’ where many more purpose made measurements could be conducted to support detailed studies of wind and turbulence characteristics in wind turbine wakes (see above, in Research Priorities). This would require a long-term commitment of funding, but is likely the most direct route to providing sufficiently detailed temporal and spatial data for model development and evaluation.

6.7 Potential Wind Energy Impact

The current uncertainty in wake model predictions is one of the major uncertainties in prediction of power output from large wind arrays. More accurate wake/wind plant models will lead to:

- Significantly improved accuracy of wake loss estimates that are used in wind array economic planning and may ultimately be used in short-term forecasting.
- More certain overall array wake loss estimates. Quantifying uncertainties is important for both wind array operation and economics.
- Better load/suitability fatigue estimates. These are needed to ensure that individual wind turbines are not subject to excessive loading which will impact component lifetimes.
- Optimized wind power plant electricity production. Ensuring the maximum energy output from each site at the lowest possible cost is crucial to the success of individual projects and to the overall energy demand goals.

It should be clear that improving predictions of energy output by adjusting locations or turbine spacing may increase the energy output from wind turbines or a wind plants by a few percent or less. However, in real terms this has a very large impact on an investment. For example, in a modern 200-wind turbine array, decreasing wake losses from 15% to 14% could mean an increase in annual output of about 10,000 MWh, and if each kWh is worth $0.10 to the producer, the net difference is over $1 million a year. Similarly, if the mean wind speed experienced by each turbine in the same wind array were increased by 0.1 m/s the net present value of the project will increase by approximately $20 million. The key result required is better match between model predictions and observed power and reduced uncertainty in power prediction.

6.8 Key Events and Approximate Timing

“The United States reported a record 5,244 MW installed in 2007, more than double the 2006 figure, accounting for about 30% of the country’s new power-producing capacity in 2007. Overall U.S. wind power generating capacity grew 45% in 2007, with total installed capacity now standing at 16.8 GW” (www.ewea.org). Given this significant growth, there is an urgent need to solve some basic research issues which could assist the successful development of wind arrays in areas now considered marginal. By reducing uncertainties, wind array economics can be improved, driving down costs and ensuring a continued high level of development. The wind energy capacity installed in the United States in 2006 was worth $4 billion. Continuing success of this industry should be seen as top priority for energy research.

Specific milestones should include:

- Identify wind plant data partners by early 2009
- Develop methods of protecting proprietary data and enabling industry buy-in by early 2009
- Wind plant data collected within 3 years and model validation within 5 years
- Wind plants designed with new tools demonstrate improved performance – immediately following design with new tools.

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7. Planetary Boundary Layer Research and Development

7.1 Abstract

To reduce the cost of wind energy from the micositing and wind plant deployment perspective, the community needs to improve their ability to predict the wind field spanning typical utility-sized turbine swept areas (50 – 200 m above ground level). Key complicating factors include: impacts of atmospheric stability, orography, and land-surface characteristics on turbulence statistics and structure. Improved prediction of these key factors and their short- and long-term influence on atmospheric turbulence will provide direct guidance towards individual turbine placement and deployment of a farm as a whole. Improved predictions of wind shear, extremes and turbulence will also allow for better fatigue and extreme load calculations. With this information, optimal financing packages and turbines specifically designed to withstand site conditions can be obtained, along with proper placement of turbines leading to lower costs of energy production.

7.2 Problem

To improve upon the current strategies for turbine micrositing and within-array placement, there are significant outstanding challenges within PBL research that require solutions in order to reduce the uncertainty associated with wind plant development. One key issue is that today's turbines are operating in the 50 – 200-m portion of the lower atmosphere; a region that is difficult to observe with traditional instrumentation and therefore has not been well sampled. It is also important to note that proper characterization of this region of the atmosphere requires wind measurements on long and short timescales to a very high degree of accuracy and precision, which is not generally required for standard weather forecasting.

Parameterizations. Parameterizations of PBL turbulence assume spatial homogeneity in the horizontal direction and only provide estimates of the average state of the mean and turbulent flow fields. Turbulence in the PBL is a highly complex three-dimensional and time-dependent entity, and turbulence structure evolves dramatically based upon the mechanisms currently responsible for its generation and maintenance (e.g., atmospheric stability, interactions with water waves, orography, or tall vegetation). Not only does the generation mechanism change the turbulence statistics, but the structure of the turbulence also changes dramatically from when generated largely by buoyancy to that generated mostly by shear (e.g., Moeng and Sullivan, 1994). The character changes yet again at night when buoyancy inhibits turbulence, the dominant length scales become independent from the distance from the ground, and mechanisms responsible for generating the turbulence can be far away (e.g., the breaking of waves on the underside of a low-level jet, or an upstream disturbance like a building or a hill).

Complex orography. Wind turbines are frequently deployed in regions of undulating topography to take advantage of the expected speed-up of wind as the atmosphere is forced up over the hill. While this reasoning is quite simple for an idealized isolated hill in a non-stratified environment, the orographic and thermodynamic impacts on the PBL are extremely complex. Turbines placed on these hills complicate the fluid dynamics yet again due to the ability for turbine-induced pressure drag to modify the appearance of topography to flow. Placement of any individual turbine cannot be performed without consideration of the turbines making up the entire wind plant. Choosing the best location for an individual turbine in such complex terrain requires a detailed understanding of the local topography, the wakes of the other turbines in the farm, and the impact of diurnally evolving atmospheric stability on the turbulent structure as a function of wind direction, and impact of tall vegetation located over the hill on turbulence and its structure.

Vegetation. Thirty percent or more of the Earth's land surface is covered by vegetation. It is well known that tall vegetation can act to reduce wind speeds, increase turbulence intensities, and modify the turbulence structure and atmospheric stability (e.g., Finnigan, 2000). Wind plant developers have traditionally avoided vegetated regimes for these reasons. However, many communities are pushing the industry to shift into these regions because vegetation blocks the turbines from view. There is a tremendous potential for further wind energy development in these vegetated regions, but accurate prediction of the expected wind field is required. Current numerical modeling strategies used in site characterization for wind energy resource assessment and wind plant siting do not accurately capture the influence of tall vegetation on the predicted mean and turbulence fields.

Wind plant under- performance. Another key outstanding issue in array micrositing is the fact that current wind plants can often under-perform predicted performance by more than ten percent when designed with the current generation of siting tools. Individual turbine placement within a wind plant is typically determined by infrastructure requirements and potential mean energy capture predictions using numerical models that inaccurately predict impact of momentum absorption, energy extraction, and wake generation from upstream turbines. Isolated wind plants appear to the flow much like a windbreak or a forest edge, as a sharp change in roughness distributed both vertically and horizontally. For windbreaks or forest edges, the speed and distance downstream required for the mean flow and the turbulence to equilibrate depends on the drag element density distribution (see for example Patton et. al, 1998 or Dupont and Brunet, 2008) and likely also depends on atmospheric stability. Therefore, consideration for individual turbine placement or operation within a wind plant or other strategies could serve to increase the efficiency of the plants as a whole.

7.3 Needs from Computation/Theory

7.3.1 Theories and low-dimensional models

Flat terrain. Wind plant and wind turbine wake models are in general about 20 years old. While improvements have been made, the timing is optimal for utilization of more intensive models such as computational fluid dynamics (CFD) codes and mesoscale models like those used in weather forecasting being brought to bear on issues relating to resource and load forecasting. Standard Monin-Obukhov similarity theory (MOST) describes wind speed profiles up to 50 m, but does not perform adequately at heights between 100 – 200 m. MOST also makes some important and limiting assumptions, the key of these assumptions being that terrain and forcing fields driving flow are horizontally homogeneous. Assumptions of this sort dramatically limit the applicable range of these low-dimensional models. Cuxart et al (2006) recently demonstrated that the currently available simple formulations perform quite miserably for nighttime stably stratified conditions (Figure 10). Studies testing similar single column models and their ability

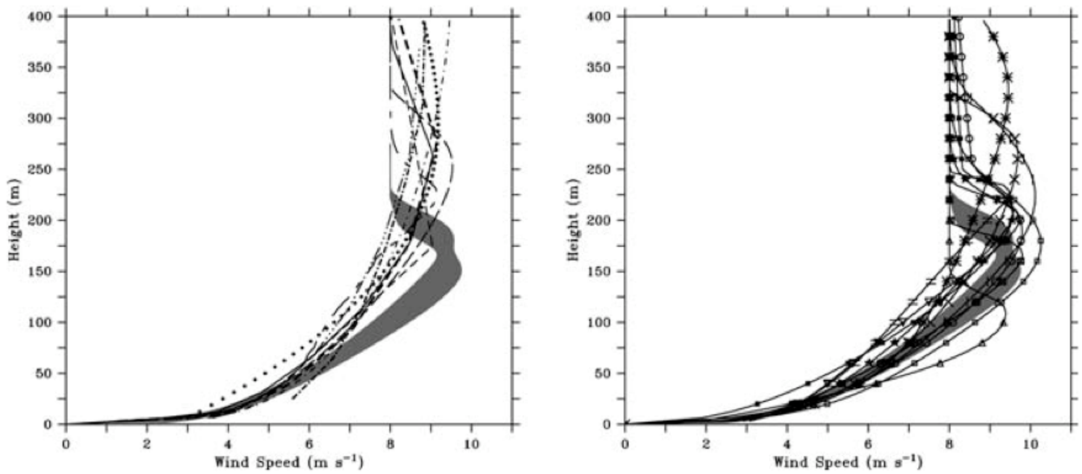

Figure 10: Predicted mean wind profiles from a range of one-dimensional column models attempting to reproduce a stably stratified PBL. The profiles on the left are first-order parameterizations, and those on the right are higher-order parameterizations. The shaded profiles show the range of results from 15 different turbulence-resolving large-eddy simulations responding to the same forcing. From Cuxart et al, 2006.

to predict a single diurnal cycle perform equally poorly (Svensson et al, 2008). Model improvements to accurately predict vertical profiles of mean and turbulent quantities under a wide variety of atmospheric stabilities are essential. Taking advantage of recent improvements to MOST that account for the enhanced mixing associated with vegetation (Harman and Finnigan, 2007) might be useful for capturing effects of a wind plant itself.

Orography. Several theoretical formulations exist for capturing the essence of flow over hills (e.g., Hunt et al., 1988, HLR hereafter). While theories like HLR are extremely useful, they are typically linear analytic solutions that are only applicable to flow over low-hills with limited thermal stratification. The Wind Atlas Analysis and Application Program (WAsP) is one of the most utilized tools to extrapolate tower-based wind measurements to a potential wind plant site and is based on similar assumptions, and is therefore equally limited (Bowen and Mortensen, 2004). The utility in models like WAsP that are based upon linear formulations lies largely in their computational speed; they include a significant portion of the physics, but can also produce results with limited computational cost. However, their utility falls off rapidly when applied in relatively steep terrain or if the weather fluctuates much. Several non-linear formulations have been developed (e.g., Xu et al, 1994) that allow for turbulence prediction in steeper terrain. These formulations are more costly than their linear counterparts, but provide more accurate results. Few, if any, formulations being utilized for micrositing or wind plant deployment in hilly terrain properly account for the influence of thermal stratification, tall vegetation, or the turbines themselves.

7.3.2 High-fidelity simulation

A key limitation with the above mentioned theoretical and modeling frameworks is that they only predict mean and turbulent statistics. Decidedly different turbulent flow fields can generate similar statistics. Wind turbines rarely operate in an average flow field. Rather, they regularly operate in the instantaneous flow field riddled with organized structures that are evolving on time-scales from seconds, to hours, up to days and with length scales ranging from millimeters up to kilometers.

Computational capabilities are now allowing for the use of turbulence-resolving calculations using tools such as DNS or LES. DNS directly solves the Navier-Stokes equations and resolves all scales of motion from the largest allowable in the domain (i.e., the domain size) down to the scales at which the turbulent energy is dissipated to heat (i.e., the viscous scales). However, because DNS relies on resolving the viscous scales of motion (~ 1mm), the largest scales of motion are limited by the available computing power; therefore, the largest length scale captured by these simulations is limited to less than about a meter. The atmospheric PBL contains much larger scales of motion, ranging from one millimeter to a kilometer or two. Because we know that in turbulent flows, the small scales are largely generated through vortex stretching by the larger scales (Tennekes and Lumley, 1972), in atmospheric LES, the Navier-Stokes equations are spatially filtered at small scales (~ 20 – 50 m) and uses a subfilter-scale model to predict the impact of the small scales of motion that are filtered out. Recently, the available computational power has allowed for computations of the entire PBL where the filter-scale sits down at about a meter (see Figure 11). Given enough resolution and a terrain following coordinate transformation, eddy-resolving simulation tools are capable of simulating flows over orography. So, high-fidelity CFD simulations are essential tools to investigate turbine-turbine interactions, stability effects, terrain effects, wind plants as a whole.

However, a limitation of these high-fidelity CFD simulations is that they are also extremely computationally intensive. So even though the computational power exists to perform these types of simulations, the wind energy industry needs answers more rapidly than is currently possible. A key vision to keep in mind is that these higher fidelity simulations need to be focused on improving accuracy of lower-fidelity simulations, and placing bounds on the resulting error bars, thereby reducing the uncertainty in the predictions.

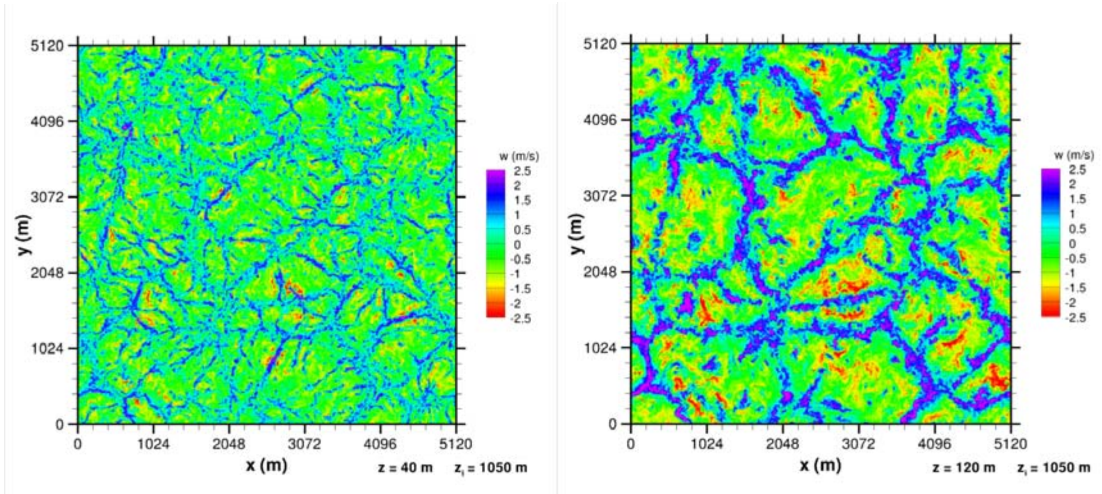

Figure 11: Horizontal slices of instantaneous vertical velocity at two heights (40 m and 120 m) from a 1024^3 gridpoint large eddy simulation of a PBL with dimension 5120 m x 5120 m x 2048 m. The simulation is forced by a horizontally homogeneous prescribed surface heating (~ 240 Wm^{-2}) and geostrophic wind (1 ms^{-1}), so the turbulence is mostly buoyantly driven and is similar to a weak wind daytime condition. To note is that even within a single stability regime the atmospheric structure varies dramatically with height. See Sullivan and Patton (2008) for further details.

7.3.3 *Boundary conditions*

These high-resolution three-dimensional and time-dependent calculations are extremely useful tools for simulating and investigating turbulence structure and dynamics in the 100 – 200-m regime in the PBL. However, there are limitations. One key limitation is the availability of realistic turbulence inflow conditions. The easiest is to use periodic boundary conditions, but this situation complicates the use of these tools when interested in flow over horizontally heterogeneous surfaces. Other methods to obtain these turbulent inflow conditions include running a separate simulation with periodic boundary conditions and taking slices of this simulation as inflow conditions for the simulation of interest. Or similarly, one could imagine simulating an extremely large domain, and recycling the fluctuations from an interior slice in the domain prior to any heterogeneity and laying those fluctuations over the top of a prescribed mean wind profile at the upwind slice (e.g., Mayor et al, 2002). While these options are quite useful for somewhat idealized situations, there is a sincere push towards nesting eddy-resolving LES within mesoscale models such as the Weather Research and Forecasting model (WRF) from NCAR to be able to investigate the influence of regional weather on local sites. Although mesoscale models like WRF are extremely useful for predicting the average state and impact of turbulence as it responds to evolving weather patterns and to the land surface, they lack the ability to capture the turbulence structure like that shown in Figure 11. Therefore, these models are unable to provide inflow conditions to an embedded LES model, which severely limits their utility within the wind energy context. Therefore, improved boundary conditions for simulations of turbulence would be extremely useful.

7.3.4 *Subfilter-scale models*

All of the simulation techniques mentioned above perform some sort of averaging or filtering of the Navier-Stokes equations and therefore require a model or parameterization describing the influence of the atmospheric motions that are lost in that process; they are typically called subfilter-scale (SFS) models. The problem is that SFS models need to evolve with the scales at which they are being applied (e.g., Wyngaard, 2004), with atmospheric stability (e.g., Sullivan et al, 2004), and with the influence of any obstacles (i.e., wind turbines) or land-surface characteristic changes (i.e., orography or vegetation) that might modify the flow (e.g., Patton et al, 2008). Improvements in SFS models for numerical simulations are essential for accurate wind plant siting and wind plant design.

Due to their minimal cost, compared to observation and/or experiment, computations are an extremely valuable tool for improved micro siting and wind plant design, but they're not nearly as useful if observations are not available to validate their predictions against.

7.4 Needs from Observations/Experiments

Significant advances could be made immediately if sufficient research effort was devoted to particular issues and combined academic understanding with extensive industry experience. In addition, research effort must be devoted to developing new measurement techniques and to providing infrastructure for the kind of long-term observations which are routinely available for other purposes, but have not yet been invested in this energy field. The purpose of developing such instruments and facilities is not only to advance understanding, which translates directly into improved energy costs, but also to participate in the world market for wind energy.

7.4.1 *Measurements in variety of terrains/locations*

Observations need to be taken in regions likely for wind plant development. Target locations for wind plant development in the United States include regions off-shore, over the Great Lakes, and regions of the Great Plains just east of the Rocky Mountains. It is essential that some of these observations be taken near (upstream, within, or downstream) of already operational wind plants, so that we can assess the impact and response of the turbines and the wind plant as a whole.

Horizontally-homogeneous flat terrain. In the Great Plains, which can be considered to be close to horizontally homogeneous terrain, one key element for wind energy is the frequent development of a low-level jet near the top of the PBL. The height of this low-level jet varies between about 50 m and 400 m, but typically occurs at about 200 m (Banta et al, 2002). There are many questions as to how the jet impacts turbine operations. In particular, if the jet forms at about hub-height, then during a single rotation of the turbine, the blades can be both within and above the boundary layer. Under these conditions, the turbines could be under extreme loads. The velocity shear on the underside of the jet generates turbulence not affiliated with interactions with the ground (Banta et al, 2003), and the momentum extraction by upstream turbines could potentially enhance that velocity shear to a critical state and generate breaking Kelvin-Helmoltz waves that could damage downwind turbines. To properly sample the rotor swept area, high-resolution (spatially and temporally) measurements of wind speed and temperature spanning the 50 – 200-m region for extended duration are essential. These measurements could be accomplished with a combination of tall-tower based in-situ measurements, or remotely sensed using something like Doppler LIDAR (see Figure 12 for example). If these measurements were to take place near or within an operational wind plant, then a number of the turbines could also be instrumented to establish direct connections between the measured winds/temperatures and the turbine response.

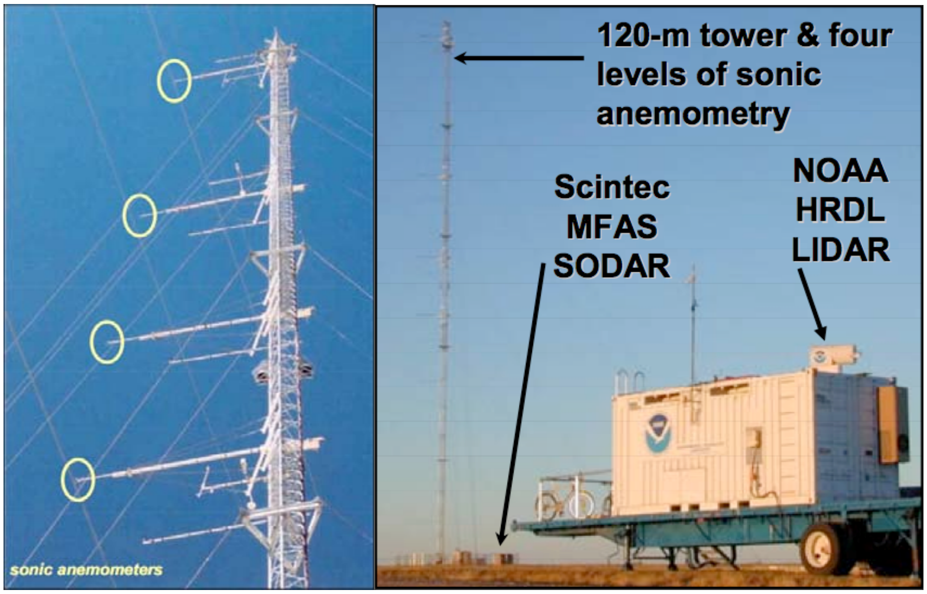

Figure 12: Sample in-situ tower measuring vertical profiles of turbulent wind components and a scanning Dopper LIDAR from the Lamar experiment (from Kelley et al, 2007).

Complex orography. Orography presents a terrifically difficult problem, generally stemming from the fact that no two hills are necessarily alike, nor are they typically similar to any idealized sinusoidal form. There are extremely limited measurements available that characterize the detailed impact of hills on turbulent flows. The wind energy industry has been placing single towers on hilltops for many years, but much of this data is proprietary and limited solely to the hilltop. A good portion of complex fluid dynamics occurs on the upwind and downwind sides of the hill. Towers on the hill top capture the net result, but not the mechanisms responsible. Mean wind direction also complicates the situation because hills are not generally symmetric. Tall vegetation on hills complicates the fluid dynamics even more because the traditional hill-turbulence interactions are modified by the vegetation-induced pressure drag. Turbines should act similarly on flow. Some think that valley channeling could be a potential for future wind plant siting, but observations are lacking. To improve our ability to site and place turbines individually and within a wind plant in complex orography, it is essential that detailed observations of turbulence characteristics be taken at numerous sites both with and without turbines.

7.4.2 Short-term versus long-term measurements

Resulting largely from financial constraints, much of the atmospheric community tends to perform observational campaigns as short-term experiments. While this style of observing is extremely useful for establishing a process level understanding, the wind energy industry needs to design wind turbines and wind plants that operate for durations more like 5 – 20 years. A campaign lasting one month or even a year at a particular site cannot pretend to capture the variability that a wind plant might encounter over its twenty-year lifetime. There is significant utility in both observational methods. It is recommended that DOE expand their capabilities to characterize numerous locations in a detailed but shorter term fashion, while at the same time establishing some longer term capabilities at a somewhat lower fidelity measurement capability. To have its greatest impact on current wind energy stakeholders, any field study would need to be carefully planned, but should be developed extremely quickly with direct input from a healthy balance of boundary layer meteorologists (some being complex terrain wind-phenomena focused and others with specific turbulence experience), canopy/soil/near-surface radiation experts, micrometeorologists/surface layer meteorologists (with shear instability experience), wind energy research focused scientists, high-resolution numerical modelers, and industry practitioners.

7.4.3 Improvements to DOE field laboratories

DOE field laboratories (like the DOE Atmospheric Radiation Measurment (ARM) Program sites) are uniquely poised to aid in the above mentioned measurement issue. These facilities have been making observations since about 1992 and have been measuring key wind variables for much of that duration. Although they're extremely useful, the focus of these measurements has not been on wind energy. Typical wind profiles are hourly-averaged and are not directed at characterizing the atmospheric turbulence that is essential for wind plant siting. Newly developing technologies such as scanning high-resolution Doppler LIDAR could be incorporated into DOE measurement suites, which would dramatically increase the utility of the ARM sites for the wind energy industry.

7.5 Impact

The major driver is to lower the cost of energy from wind plants. The research needs proposed here will reduce energy costs from wind plants through: 1) an industry-wide reduction in the uncertainty of wind speed/energy production estimates, 2) improved operations and maintenance costs, 3) improved turbine reliability, and 4) technology for improved weather forecasting that will transfer to many atmospheric applications.

7.6 Key Events and Approximate Timing

Wind energy is a fast moving business with urgent research needs. We anticipate the following: 1) immediate definition of detailed stakeholder measurements and modeling needs/locations, 2) first observatory with observations to 200-m height by 2009, and 3) AWEA/EWEA/IEA workshops comparing models with observations and describing PBL and 0 – 200-m atmospheric characteristics at a specific site by beginning 2009.

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8. Acquiring and Exploiting Large-Scale Data Sets

8.1 Abstract

To ensure future growth and cost effectiveness of wind energy, reference data sets of wind turbine behavior and the atmosphere surrounding them are needed to better understand the physics of wind energy production. Better understanding of the physics will lead to better prediction codes and less uncertainty for manufacturers and developers of wind turbines, resulting in lower overall costs of energy. Many existing data sets in the atmospheric community may not be directly applicable to the wind energy problem. But, the infrastructure used to gather them may be augmented to obtain more measurements that focus on the areas of interest for wind turbines. More measurement sites should also be developed that can measure a representative range of atmospheric conditions and topography consistent with wind plants installed in the United States. Development of new measurement sites must also be accompanied with development of new measurement techniques, as well as computational techniques for analyzing large data sets and prediction of extreme events. Finally, existing data sets in the wind turbine community, primarily from developers and operators, must be made available to researchers in order to improve models, while also protecting the intellectual property of the industry.

8.2 Problem or Opportunity

Researchers and industry need better reference data sets of atmospheric behavior and corresponding wind turbine operation to quantify the complex interaction between the wind and the mechanisms used to transform it into electrical energy. These data sets will be unique to the area of wind energy largely because current utility-sized wind turbines operate in a regime of the atmosphere (50 – 200 m above ground) that is poorly studied. Also, the requirements for spatial and temporal resolution needed to analyze detailed turbine-atmosphere interactions are more stringent than currently existing datasets can provide.

Research measurement sites and re-analysis data from the atmospheric community, such as NCEP-NCAR (Kalney, 1996) or the NOAA-NWS Wind Profiler Network (Schlatter and Zbar, 1994), have been gathering data for long periods of time, but only for relatively sparse grids around the globe or use relatively large averaging times or measure at heights well above 200 m. Augmenting or modifying such systems to gather data relevant to wind energy should be a starting step for increasing the amount of wind turbine-specific data available. Given that it is often advantageous to place turbines in areas of complex terrain because of wind accelerations due to topology, research data sets that focus on the effects of orography (Taylor, 1987) are also important. Data sets of operating wind plants in such terrain are currently not available in the public domain.

Methods for sharing wind plant operating data with the research community while also potentially protecting commercial sensitivity should be developed. Existing data sets from industry, with the exception of a few offshore wind plant operators (Frandsen, 2007), are often treated as commercially sensitive and not made available for research purposes. Also, even though the industry has access to such large data sets within their own organizations, they often lack the time to evaluate any discrepancies between predicted behavior of wind plants and actual power output. Therefore, even though operational data sets exist, they are currently not being used to advance modeling capabilities.

Finally, the accuracy of standard-design extreme events for wind turbines, such as those in the IEC design standard (IEC 2005) is unknown. These design extreme events are often based on previous experience at a few select locations and may not reflect the true extreme behavior at many current wind plant locations.

8.3 Research Approach

To overcome a current lack of reference data for typical wind turbine operating sites and atmospheric conditions, many new data gathering measurement stations should be built and currently existing stations modified. The data sets gathered from these stations should be well resolved both spatially and temporally specifically for application to wind energy problems and the stations themselves built for long periods of data collection. These data sets should be gathered through a network of measuring sites at different locations representing a range of terrains and atmospheric behavior. Methods for allowing developers and wind plant operators to share data should also be developed so that this potentially large source of data can be made available without compromising the commercial interests of the industry. Finally, special attention should be paid to extreme event analysis and measurements that can capture these rare events that often drive wind turbine design.

8.4 Needs from Computation/Theory

While this summary is mainly concerned with observations and experiments of the atmosphere and operating wind turbines, there are some areas where computational methods will be useful. The first is using computational tools to design the experiments themselves. By their very nature, extensive field campaigns can be very costly and any predictions and optimizations of the measurement set-up that can be estimated computationally first will reduce the costs of such a campaign. Experimental design questions that might be answered computationally include: what are the optimal places to place meteorological towers to measure certain atmospheric behaviors and what kind of wind turbine responses should be measured to correlate with that atmospheric behavior?

A large network of measurement sites would also produce extremely large data sets, which could be analyzed using newly developed data mining methods. These methods would search for patterns over a range of variables that may give insight into the physics of the turbine/wind plant interaction with the atmosphere (e.g., Tebaldi et al, 2007).

Due to cost constraints, the measurement network will certainly have gaps in both space and time resolution. To fill these gaps, researchers will employ advanced computational methods for interpolation and/or extrapolation which will provide more useful data to modelers for code validation (e.g., Larsén and Mann, 2006).

8.5 Needs from Observations/Experiments

The first step in creating a set of reference data sets that will be useful for the wind energy community is to assemble currently available data in a common repository with a single standard format. These data sets may provide some additional insight into atmospheric behavior not yet considered by the wind energy community, and may also provide clues as to what additional data is needed from future measurements of the atmosphere. Examples of applicable data sets from the atmospheric community include the CASES-99 (Poulos et al, 2002) and the DOE ASCOT (Dickerson and Gudiksen, 1983) studies.

A major effort should be initiated for developing a new network of measuring sites that will create reference data sets. This type of network has already been created for other large measurement campaigns, such as for cloud formation (Klein and Del Genio, 2006), solar resources (Gilgen and Ohmura, 1999), and carbon dioxide fluxes in forests (Baldocchi, 2001). Therefore, the procedures and typical costs to create such networks are readily available. Most importantly, these sites should be located in and around locations of large wind resources, where wind plants already exist or will potentially in the future. This should include a representative sample of different locations in the United States where wind plants may be located.

Figure 13: National Weather Service/NOAA Wind Profiler near Glennallen, AK.

Such a network of measurement sites can be created by starting from already existing measurement sites around the United States. Augmenting existing measurement systems such as the NOAA-NWS Profiler network (see Figure 13) to measure at lower heights or at faster sample rates will be mutually beneficial to both the wind energy sector and weather/climate measurement communities by providing more detailed measurements closer to the ground. Augmentation may include adding systems like scanning or Doppler LIDAR (Smith et al, 2006) and meteorological towers to currently existing sites. Certain sites with interesting atmospheric (e.g., low-level jet in the Great Plains) or turbine-specific behavior may be measured in much more detail depending on the type of behavior to be observed. These "super sites" may have much more instrumentation and sample at much higher resolutions over a fixed period of time.

In addition to fixed measurement platforms dispersed around the country, it will also be useful to have at least one mobile DOE measurement laboratory that could temporarily measure at sites of interest. Such a mobile laboratory could include LIDARs (see Figure 14) and SODARs and would make it easier to measure in and around existing wind plants or met towers. Mobile facilities were used in the Lamar Low Level Jet Project (Kelley et al.) and are currently being developed at Risø in Denmark (Mikkelsen, 2007). Such facilities have also shown use in measuring of wakes downstream of turbines (Barthelmie, 2003), for which very few reference data sets are currently available.

Figure 14: Mobile LIDAR systems used for wind energy measurements.

Because much of the research on wind climates related to wind energy is based on measurements of the flat terrain in northern Europe, measurement campaigns must also focus on a variety of terrains and atmospheric conditions. Areas that include complex terrain, forested topography, and offshore locations need further study. It would also be beneficial to include a greater variety of climates in the United States, such as the mesas of Texas or the high wind speed climates of the Great Plains.

Many developers and operators of wind plants have data that would be extremely useful to the research community for the purpose of model development and validation. Methods for disseminating this data among researchers should be developed to allow for exchange of this useful commodity while also protecting the intellectual property of the commercial entities. Such methods may include normalization of quantities like power production or even individual intellectual property agreements with a given set of researchers.

In creating these measurement sites, researchers will also need to continue development of new instrumentation to measure wind turbine behavior, wind, and other atmospheric quantities of interest. New measurement technologies are always being created and existing technologies improved. It is obviously advantageous to have the most accurate, yet cost-effective tools available for this task.

Until much longer-term measurements (over 10 years) of the atmosphere around critical wind sites are complete, it will be difficult to assess the accuracy of the extreme event prediction. Therefore, it will be important to plan for long-term and continuous measurements at some of these sites in order to capture these rare events. These measurements may be of lower fidelity due to cost and data collection constraints, but detailed enough to capture critical atmospheric and wind turbine behavior.

Finally, it is possible that wind tunnel measurements can offer a cheaper alternative to extensive field campaigns for some atmospheric behaviors. Wind tunnels have been shown to be useful particularly in the study of complex terrain (Ayotte and Hughes, 2004) where complicated field experiments may be prohibitively expensive.

8.6 Potential Wind Energy Impact

The creation of world-class reference data sets for specific application to wind energy will have immediate impacts. Currently, there is very little data available for validating and improving the primary models used for micrositing of wind plants. The data that does exist is predominantly from land based sites in northern Europe and European offshore sites. Having new data available that reflects the atmospheric and topography effects commonly seen in the United States will lead to more accurate models for these applications and lower the uncertainty and risk for wind plant developers in the future. Given that many wind plants in the United States are currently under-producing by as much as 10%, the faster these data sets can be made available, the better. In addition, assuming that useful data can be extracted from existing data sets, new value will be added to these data sets by applying it to the wind energy arena. Similarly, new data sets created specifically for wind energy can be applied to other important areas of atmospheric research outside of wind.

8.7 Key Events and Approximate Timing

Developing a large long-term network of measurement sites will take many years to plan and execute. Some immediate goals for the development of reference data sets include:

- Identify collaborative partners in building a large-scale measurement network to leverage funds and ease construction costs immediately (e.g. ARM, AWEA, NASA, NOAA NWS, Risø)
- Locate and aggregate appropriate existing datasets by 2009
- Commit funds immediately and begin development of DOE observational laboratories by 2009
- Augment NOAA NWS Wind Profiler Network by 2010.

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9. Technology Transfer and Tool Integration

9.1 Abstract

To enable continued rapid growth of the wind industry, researchers and industrial partners need to accelerate the pace of technology transfer and tool integration between their communities. In the commercial sector, the current generation of design tools is grossly inaccurate for micrositing needs. Tools designed in the research sector can be applied to wind engineering specific applications, which will increase the accuracy and reduce the risk for developers. Validation data unique to wind energy must be acquired in order to ensure improved accuracy. Often, this data comes from commercial wind plant operators, and due to competitive sensitivities, methods for protecting proprietary data should be developed. Improved technology transfer and tool integration will increase the accuracy of industrial design tools and lowering the cost of energy.

9.2 Problem or Opportunity

Wind energy continues to be the fastest growing energy technology in the world, with a 27% growth in installed global capacity during 2007 alone (GWEC, 2008). And with large projected growth in the coming decades, this rate will likely continue for the foreseeable future: "Areas with good wind resources have the potential to supply up to 20% of the electricity consumption of the United States." (Bush, 2006). The transfer of modeling capabilities from research to industry in the micrositing area needs to be accelerated to keep up with both industry growth rates and DOE research goals.

Because of the rapid increase in installations, the wind industry has little time to incorporate research advances made in academic and laboratory settings, which may lead to drastic improvement in designs and overall cost of energy for power production. This is particularly true in the area of micrositing and array effects where under-production of wind plants can be directly attributed to the immature models used by industry to design them. The large uncertainty in commonly used micrositing models such as WAsP (Mortensen, 1993) can lead to higher risk for investors and economic penalties to developers for under-producing wind plants. Also, developers using existing tools are unaware of uncertainties in the current generation of models, which may lead them to apply models outside of their intended usage. Given large research investments in the atmospheric sciences in recent years, incredible opportunities exist to transfer technology from research endeavors to industry that will lower the cost of energy from wind.

Often, even if these atmospheric tools exist, they are not optimized for wind resource analysis and also not integrated with wind turbine design tools. Future efforts should concentrate on integrating models from the atmospheric science community with commonly used tools in the wind turbine design community.

9.3 Research Approach

The approach for accelerating transfer of technologies from the research community to the wind turbine industry is part logistical and part research. Research is needed on how to apply atmospheric science tools (e.g., Moeng and Sullivan, 2002) and integrate them with wind turbine design tools (e.g., Jonkman and Buhl, 2005) to improve the accuracy of micrositing methods. The quantification of the inherent uncertainties in both existing and future design tools will also be an important part of future research. Currently, the magnitude of these uncertainties is unknown, but can have a dramatic influence on decisions related to micrositing and power production.

Logistically, it will be important to increase communications between the atmospheric and wind turbine communities. One way to accomplish this is through special sessions at respective conferences. In the wind turbine community, this would include a special session at the AWEA Windpower or AIAA/ASME Wind Energy Symposium focused on PBL modeling. In the atmospheric community, pertinent conferences that could introduce a wind turbine session are the American Meteorological Society's Boundary Layers and Turbulence Conference and the American Geophysical Union's annual conference.

Finally, developing methods for protecting proprietary data while also ensuring its availability for publication will be important for benchmarking and validation of all models used in the community. Such methods could include normalizing the data so that absolute values are not revealed, or creating agreements with individual researchers that will use some parts of the data to validate their models, but not publish the commercially sensitive aspects.

9.4 Needs from Computation/Theory

Research efforts should be undertaken to improve lower fidelity models used by the industry. These models will have run times consistent with a typical industrial design cycle (several days), but with improved accuracy over the current generation of tools. Currently existing codes in the atmospheric science and wind turbine design community must be integrated into single packages to provide closely coupled modeling capabilities. How to best interface these codes is a research topic in itself, but seamless interfaces will lead to more consistent interoperability between these currently separated regimes. Better coupling will also reduce the amount of operator error that can be a significant contributor to the overall uncertainty of wind plant predictions.

In addition to improving precision and accuracy of wind production and load estimates, major effort is needed to include the known uncertainty in all stages of design and operation. This can be done by performing very detailed sensitivity studies, where the input parameters are varied probabilistically and the influence on output parameters is quantified and correlated back to the inputs. Quantifying uncertainties will give future users a better understanding of how uncertainty of inputs influences the associated outputs, and also the relative importance of certain parameters.

9.5 Needs from Observations/Experiments

As modeling capabilities are transferred from the research community to industry, more validation data will be needed to ensure models are more accurate than the current generation. This validation data will involve unique measurements of the PBL and in and around wind plants and turbines. Existing data should be combed for potential applications to wind resource characterization. Once current data sets have been exhausted, measurements of the PBL need to be performed in areas that have been overlooked by the atmospheric science community;

between 50 – 200-m height above ground, which are typical hub heights for utility sized turbines. Also, the effects of turbines on the atmosphere and other wind turbines within a wind plant need to be quantified. This entails simultaneous measurements of wind fields upstream and downstream of individual wind turbines and wind plants. Operational data of turbines within these plants is also necessary to correlate with wind field measurements and improve validation efforts. Of course, developers may be reluctant to release such data to researchers wishing to publish, and in response, methods for protecting or sanitizing such data must be developed.

9.6 Potential Wind Energy Impact

Improving links between the research community and industry is an essential part of building a successful industry. Improved technology transferred between the communities will result in more accurate design tools for the commercial sector. These design tools will also be more closely integrated and reduce the uncertainty of wind plant production estimates. It may also increase the possibility of design tools used for site-specific design, where turbines and plants can be optimized for a given location and the cost of energy lowered relative to more generic designs. Finally, technology transfer and tool integration will result in greater likelihood of DOE research goals.

9.7 Key Events and Approximate Timing

To encourage the science behind wind energy to improve and to ensure technology transfer some early goals should be:

- Micrositing and array effects code workshops at industry events (e.g., AWEA, EWEC etc.) starting in 2009
- Develop methods of protecting proprietary data, enabling industry buy-in by early 2009
- Wind plant data collected within 3 years and model validation within 5 years
- Wind plants designed with new tools demonstrate improved performance – immediately following design with new tools.

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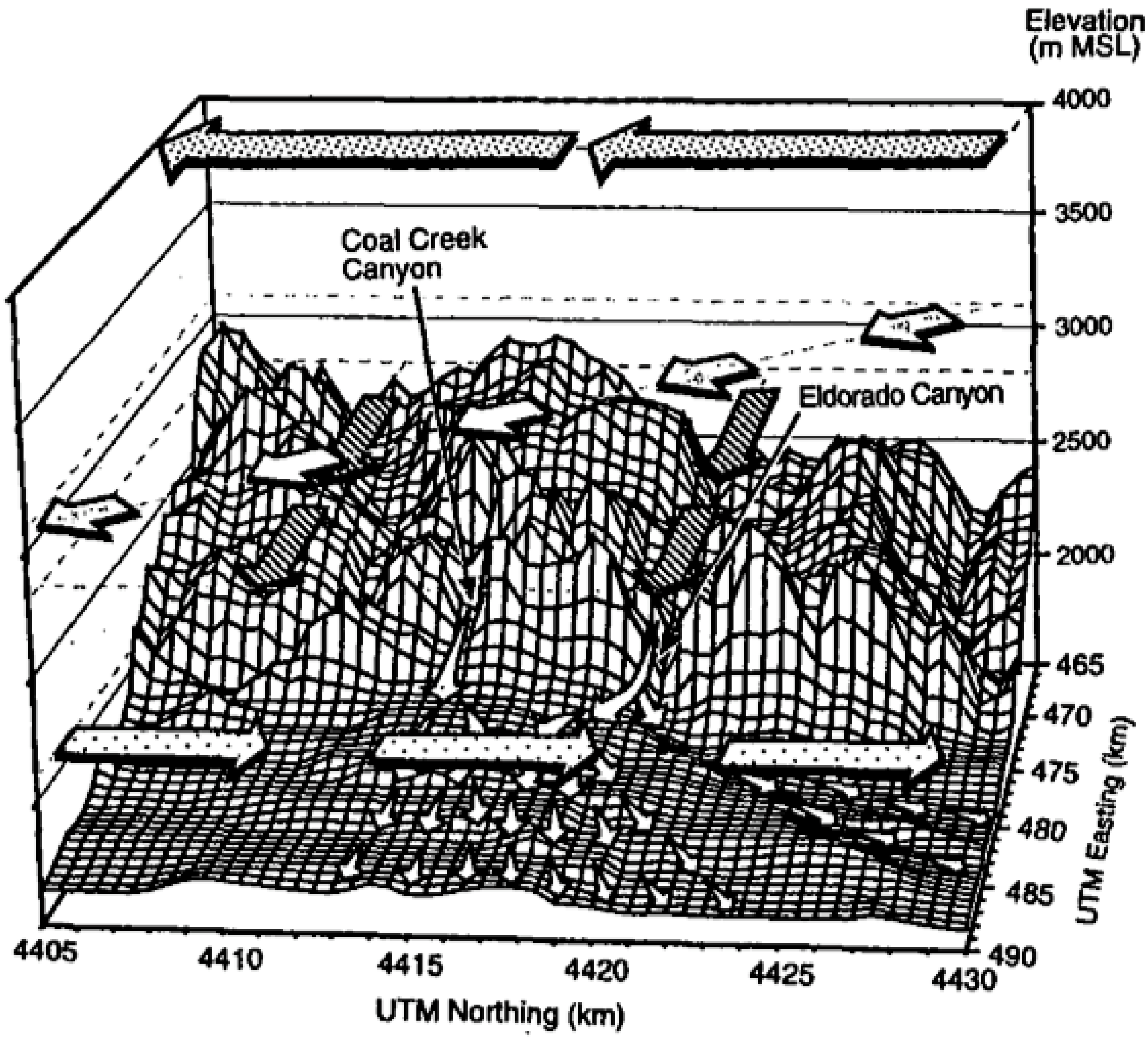

10. Wind Energy Testbed Development

10.1 Problem or Opportunity

At present, data sets that adequately address characterization of the atmospheric boundary layer structure for wind energy development do not exist. Better data sets would allow for the resolution of several key wind energy development barriers that include:

- Lack of understanding of the range of inflow turbulent field conditions (including coherent structures) and their effects on power performance and machine loading
- Lack of knowledge of the characteristics and frequency of occurrence of extreme meteorological events that contribute to the early failure of wind turbine components
- Significant uncertainty in the accuracy of mesoscale and microscale meteorological models that could be used for predicting wind resources
- Uncertainty in the accuracy of using mesoscale meteorological models for predicting, in real-time, changes in wind energy production associated with transient weather systems
- Uncertainty in the ability of climate models to predict wind energy resource variation under various climate change scenarios
- Where concerted measurement campaigns have occurred, the duration is typically too short to obtain good climatological averages.

The reasons for the lack of adequate data are varied. They include the fact that most long-term, high temporal resolution measurements come from surface meteorological stations that are not representative of winds in the layer from 25 – 200 m, where most wind turbines reside. For winds aloft, the NOAA/NWS national radiosonde network of ~100 sites provides vertical profile wind information, but only twice daily, with a vertical resolution of ~ 25 m. This antiquated system is in the process of being replaced with the Radiosonde Replacement System (RRS) that uses new technology allowing for wind measurements with a higher vertical resolution. However, because balloon systems make point measurements in space and time, the representativeness of winds from these systems is poor, and they do not provide turbulence data. In addition, NOAA maintains a sparse network of 404 MHz wind profilers in the central United States, but the lowest level winds provided by these profilers is ~500 m, and therefore of limited utility for wind energy.

Various government agencies also operate on the order of ten to twenty 915 MHz wind profilers in the United States. These profilers typically have a lowest range gate of approximately 100 m, with additional range gates at 60 to 100-m intervals above that, providing at most two or three measurements at turbine levels. Although of more potential use for wind energy, they still are not capable of addressing all of the meteorological issues hampering wind energy development. Wind profiles also can be derived from velocity azimuth display (VAD) scans from NOAA's national network of WSR-88D weather radars. However, the lowest VAD range gate is approximately 300 m, with a 300- m vertical resolution, which again leaves them unsuitable for most wind energy applications. Finally, there are a very limited number of tall towers in the United States that have been instrumented with meteorological sensors. Most of these towers are less than 60-m tall, while several (perhaps no more than 2 or 3) reach 200 m. It is unknown at present how many of these towers record continuous measurements, if there are large temporal gaps in the historical data, if the data are readily available, what types of measurements are taken, and how accurate the data are.

10.2 Research Approach

One solution to the need for better meteorological observations is to develop Wind Energy Testbed sites**.**

- The goal of the Wind Energy Testbeds is to accelerate the development of wind energy through use of new technologies from the atmospheric and wind energy research communities. This includes deployment of advanced tools (new observational systems, as well as weather, turbulence, and turbine prediction models) in a testbed setting where they are continuously refined, demonstrated, and evaluated.

- The focus of the observations collected at each testbed would be a domain as large as 20 x 20 km, and the layer from 20 – 200 m, which is poorly observed by current operational measurements, but essential for wind energy.

The testbed sites would center on long-term deployments of state-of-the-art instruments that provide the measurements necessary to 1) measure the turbulence intensity and wind shear profiles that affect the reliability and longevity of wind turbines, 2) evaluate and improve low-level wind simulations in microscale, mesoscale, and climate models, and 3) evaluate instruments that might commonly be deployed at potential wind energy sites.

A requisite component of the testbed development is coordination with the atmospheric modeling (microscale, mesoscale and global climate scale) community. In particular, it is essential that observations be taken that are necessary for the initialization and evaluation of the models, as well as for parameterization development. In addition, model evaluation should be a continuous process, allowing for iterative improvements in both the observations and models. Also, it needs to be assured that resources are available for analysis and application of the testbed data, not just its collection.

Ideally, there would be testbed sites at multiple geographic locations. This would allow for the achievement of regionally varying objectives. Requirements for the testbed program include that they measure 1) the central plains low-level nocturnal jet, 2) winds in complex terrain such as the Appalachians and Western U.S. mountains, 3) winds near operating wind energy projects, and 4) coastal wind processes, preferably at an offshore site. It is possible that the instrumentation for a testbed site could be moved to a new geographical location after some period of time. However, as measurements of at least several years are probably required at each site, this would delay the acquisition of data at some geographic locations where it might be of immediate use. We also note that the DOE ARM Southern Great Plains facility in Oklahoma would be an obvious candidate location for a site that focuses on the impact of the low-level jet.

10.3 Needs from Observations/Experiments

The emphasis of the testbed is on the lower PBL, from the surface to approximately 200 m. We need to make accurate measurements in conditions up to ~30 m/s, primarily of wind velocity and turbulence profiles, but also stability (temperature profiles). All instrumentation systems have their strengths and weaknesses, and no single system will measure all of the parameters necessary for wind energy development. The depth of the PBL will be important for scaling laws, parameterization development and model evaluation. Except in exceptionally homogeneous terrain, it will be essential to have measurements at multiple nearby locations, as any single site will, in general, not be representative of the larger area. For example, what is measured at the crest of a hill/ridge will be very different from other nearby locations.

10.3.1 In-situ

Tall towers instrumented with multiple levels of sonic anemometers, cup anemometers or propeller vanes, and temperature sensors are ideal in many aspects for wind energy studies, as they provide high accuracy measurements of wind and turbulence at high vertical and temporal resolution. However, towers are expensive to build, with the cost increasing exponentially as the height of the tower increases. In complex terrain, towers only provide a measurement at one horizontal location.

10.3.2 Remote sensing

LIDAR. LIDAR's have been successfully used in recent wind energy studies. The advantages of LIDARS are that they provide accurate, high resolution wind measurements. The only inherent spatial resolution limitation of the LIDAR is associated with the path averaging along its pencil beam, which is approximately 30 m. Each radial Doppler beam measurement takes on the order of 1 s, and in approximately 30s a vertical scan can be made providing a very vertical high resolution profile of radial winds. In addition, by staring at one elevation angle, time series of the turbulent winds can be made at the different range gates along the beam. Also, LIDARS are not limited by ground clutter.

Wind profiling radars. The biggest problem with 915 MHz boundary layer wind profilers is their coarse vertical resolution (~60 m) and their lowest range gate (~80 – 100 m). A new high-resolution Range Imaging (RIM) multi-frequency technique is being developed, which could potentially provide vertical resolution on the order of 10 m. However, the lowest range gate of a RIM 915 MHz wind profiler would still be about 80 m. Spaced array antennae profilers have the advantages that they measure a single column directly above the radar, and provide rapid updates of the wind profiles approximately every 30 – 40 s. However, the vertical resolution and lowest range of these systems is about the same as a standard 915 MHz wind profiler. Tests have been run on a RIM spaced-array antennae profiler, producing higher vertical resolution data, but with the first range gate still on the order of 80 m. Additional testing and validation of RIM and spaced antennae winds is necessary. Wind profiling radars also provide excellent depiction of the depth of the convective atmospheric boundary layer, and wind profilers with Radio Acoustic Sounding System (RASS) also measure the vertical temperature profile, although with the same lowest range gate and height resolution limitations as for winds. Finally, one potentially major shortcoming of wind profiling radars is that ground clutter generated by the moving wind turbine blades would require that the profilers be located over the visual horizon from the turbines.

SODAR. These instruments can provide high-resolution vertical wind profiles, from the surface to 300 m. Their greatest limitation is that for wind speeds greater than about 15 m/s, the quality of the data rapidly degrades as the sound pulse is advected too far downstream of the receiver, and ambient noise from the wind blowing over the SODAR hardware and nearby obstacles overwhelms the desired meteorological signal.

Satellite. These provide surface wind measurements, but only over water.

10.3.3 Supporting instrumentation

In addition to mean wind, turbulence, and temperature profiles, supplementary measurements are needed to support the development and evaluation of atmospheric models. Parameters to be measured would include solar and net radiation, soil moisture and temperature profiles, PBL depth, surface heat and moisture fluxes, and the large-scale pressure fields.

10.4 Potential Wind Energy Impact

A successful Wind Energy Testbed program would:

- Remedy the serious lack of long-term consistent data at the scales of interest.

- Generate research interest at a wide range of public and private institutions. The data sets created by this observational effort would be unique in their scope and duration. Graduate students and other researchers would be able to conduct experiments using the “ready-made” data rather than having to collect their own.

- Provide data to develop more sophisticated power curve specifications, improve turbine wake modeling, identify mechanisms of structural loading, and research optimization of machine control algorithms for maximizing wind resource capture and minimizing structural loading.

- Provide for the evaluation of models under the full range of atmospheric conditions. Sustained measurements at a few geographically diverse sites, each of which experiences a commercially viable wind resource, will result in a rich set of data spanning a full range of operating conditions. These data can then be used to assess performance and uncertainty in models at relevant time-length scales.

- Lead to development of improved models that would generate better wind resource information on annual, seasonal, diurnal scales for improved site design, reduced uncertainty in energy estimation, and increased performance of operational weather forecasting. Improved models, once developed, have the potential benefit of reducing the number of measurement sites and/or the amount of time required to characterize the wind resource at candidate project sites, both of which readily translate into economic advantage.

- Promote the development of coupled models operating across typical application scales (e.g. coupled mesoscale-LES models) and enable iterative experimental design combined with development and validation of models. Closing the gap between the time-length scales of the turbine and the mesoscale atmosphere is an important objective for the wind energy industry.

- Allow for the development of instrumentation specifically suited for addressing critical observational gaps for wind energy development (e.g., high resolution winds, turbulence intensity and thermal stratification).

10.5 Key Events and Approximate Timing

- Develop programmatic collaborations with other agencies and institutions that have overlapping missions relevant to wind energy development and that could contribute resources to the Wind Energy Testbed. (Timing: Immediate)

- Form a team of meteorological observation and model experts, turbine experts, and wind energy developers that will determine the highest priority presently existing instrumentation and prioritize the Testbed region(s) so we can maximize the effectiveness of the Testbeds with limited funds; and then establish funding**.** (Timing: Immediate)

- Identify new instrumentation specifically suited for wind energy studies that potentially could be developed for this program. (Timing: Within 3 months after funding for the program is established)

- Select the Testbed sites and obtain land leases. Ensure that basic infrastructure at the sites is available (power, communications, etc.) (Timing: Within 6 months after funding for the program is established)

- Begin acquisition and testing of instrumentation for the Testbeds. (Timing: Within 6 months after funding for the program is established)

- Deploy instrumentation at the Testbed sites. (Timing: Within 12 months after funding for the program is established)

- Initiate model evaluation studies. (Timing: Within 12 months after funding for the program is established)

- Revise experimental plans based on measurement findings and results from model evaluations. (Timing: Ongoing)

An auxillary task is to form a team to categorize and make readily accessible historical data sets that may be of use for wind energy development. This would include an assessment of the quality and accuracy of the data sets, and may involve attempts to surmount legal and intellectual property barriers to data sharing. (Timing: Complete within 12 months after funding for the program is established)

11. Improve Industry and Atmospheric Modeling

11.1 Problem or Opportunity

Wind energy applications require meteorological information on a variety of time and space scales, most critically the wind speed and turbulence at the height of the turbine rotors. Because wind power is proportional to the cube of the speed, accurate predictions are essential. Important forecast periods include:

- Near real time, from a few minutes up to one hour ahead, to provide alerts on severe weather events which could significantly change the output of the regional wind capacity and affect system reliability.
- One to several hours ahead, to anticipate rapid changes in output from a wind plant to the regional electrical power grid and the need for scheduling adequate reserve capacity to accommodate up and down movements in the wind plant output.
- One to several days ahead, to anticipate the need to start or stop large fossil-fueled units, which have long start-up times and lengthy down times between start-ups, in order to accommodate the diurnal weather patterns and the passage of weather systems.
- Climatological spatial variability of wind properties at relatively fine spatial scales, to assess topographical enhancement or degradation of the wind resource for planning and siting.

Forecasters generally rely on numerical weather prediction (NWP) models, which are available on a wide range of scales. Daily weather forecasts and climate predictions use mesoscale and global models, whereas at the other extreme, research models that may only cover a few hundred meters or a kilometer are able to resolve atmospheric motions down to a few meters; such models are used to study turbulence properties. Mesoscale models employ grid spacings typically between 1 and 30 km and have domains as small as urban areas or mountain valleys and as large as a continent.

Mesoscale meteorological models are now being used routinely to produce weather forecasts. The output of these models is also used to drive dispersion, chemistry, and hydrology models. More recently, mesoscale models have been used for the wind energy community to map regional and national wind resources, determine the most suitable sites for wind turbines, and provide short-term and long-range forecasts that support wind turbine operations and aid the utility industry to efficiently integrate wind resources into the power grid, as described in the first paragraph. Mesoscale modeling is attractive because it is a relatively inexpensive means of estimating the wind characteristics over large regions, compared to the expense of deploying meteorological instrumentation at a large number of locations. Because of the particular requirements of the wind energy industry for quantitative output, it is important to consider the accuracy of current-generation NWP models.

11.2 Need for Theory and Engineering

NWP models of today are complex and remarkable computer codes, capable of considerable skill in predicting the future state of the atmosphere. Larger-scale models can be used with skill to predict weather, and mesoscale models can often produce wind fields in complex topography and coastal zones that resemble observed winds. Numerous studies over the past three decades have described the performance of mesoscale models and have noted that their ability to predict overall weather conditions has continually improved. The skill in predicting evolving synoptic weather is acceptable in many situations, but the details of predicting mesoscale features continue to be a challenge for such models.

The critical question becomes, what is being asked of NWP models for wind energy applications? Accurate predictions of wind speed for several hours and for one to a few days, accurate predictions of when severe weather will strike a plant, accurate representation of the spatial variability of the wind resource over many different distance scales for siting and planning, and accurate characterization of atmospheric turbulent fluctuations are some requirements mentioned previously. The current generation of NWP models has not been optimized to address these needs. To be sure, model output would represent a considerable improvement over many engineering practices, for example, use of the power-law wind profile, but the wind industry requires much more detailed and accurate information and predictions of wind to use this resource most effectively. Obtaining these kinds of high-quality information from NWP models is possible, but will require improvements over current capabilities in many areas.

Atmospheric phenomena that affect near-surface winds of interest to the wind energy community include low-level jets, complex terrain / coastal circulations, boundary-layer processes, and severe convection. Mesoscale models have been shown to qualitatively capture many of the characteristics of these atmospheric phenomena. However, relatively large errors still exist with the timing and magnitude of the mean winds associated with these phenomena, the interaction of the synoptic and smaller-scale flows, and the timing and location of severe convection. For example, the speed, height, and vertical profile characteristics of the nocturnal low-level jet, an important wind resource in the Great Plains of the United States, are not well represented in mesoscale models. Accurately representing boundary layer properties, such as turbulence, is also difficult for mesoscale models, especially during nighttime stable conditions. Relatively large errors in the predicted near-surface wind speeds, wind directions, vertical wind shears, and turbulence are normally not very important for routine weather forecasts, and thus have not received as much attention as severe weather (e.g. precipitation, thunderstorms, hurricanes). These errors, however, significantly impact the wind energy community.

Increasing computing power using Linux clusters of tens to thousands of processors has enabled meteorological models to be run with smaller grid spacing, so that many small mesoscale phenomena are explicitly resolved. Although additional computational resources have proven very useful, they do not solve all of the problems associated with wind predictions. Most of the forecast errors can be attributed to inadequate representation of modeled processes, including the parameterized treatments of atmospheric processes occurring at length scales less than those resolved by the model. Fundamental knowledge gaps need to be addressed in order to provide improvements to these parameterizations, thereby improving wind field forecasts.

New and improved theories based on measurements are needed for a range of small-scale atmospheric processes. Additional research, coordinated between observational researchers and modelers, is needed in the following areas:

- Representation of stable mixing and stable boundary-layer processes
- Atmospheric radiative flux divergence in the boundary layer
- Improved theory describing the relationships that couple the heat, moisture, and momentum fluxes in the atmospheric surface layer with the ground
- Treatments of surface roughness elements, such as variations in vegetation, urban canopies, and turbines in a wind plant
- Characterization of the vertical exchange of heat, moisture, and momentum within the PBL
- Cloud parameterizations that can more accurately predict downbursts associated with severe weather.

Cloud parameterization development is already an active area of research in NSF and NOAA; therefore, new information from these agencies needs to be transferred to wind energy modeling. In contrast, relatively little organized research is being pursued in the other areas that warrant a larger and more coordinated effort.

Another fundamental problem for meteorological modeling relevant to wind energy applications is the appropriate spatial scales that models have been designed for. Mesoscale models contain parameterizations that are valid using grid spacings as small as approximately 1 km. LES models, that employ different turbulence closure methods, have been designed for spatial scales less than 100 m. It is desirable to predict variations in winds on spatial scales less than 1 km but greater than 100 m to resolve smaller scale variations in terrain and other surface roughness elements, including the interactions among turbines in wind plants, which affect local wind fields. Although mesoscale models can be run with grid spacings smaller than 1 km, they should not be used in this way because the current parameterizations are not valid at those scales. Therefore, turbulence closure and other parameterizations that enable models to employ grid spacings between 100 and 1000 m with valid parameterizations are needed to better estimate local wind variations for the wind energy industry.

In addition to the need for improved theory, methodologies on how to best run and evaluate models need to be improved and developed including:

- Data assimilation geared towards wind energy applications that include rapid update cycles and assimilation of turbulence measurements
- Better characterization of “extreme events” from mesoscale model forecasts
- Determining how to specify and interpret uncertainty for applications,
- How to best employ ensemble modeling given that models have biases that cannot be corrected by averaging ensemble members
- Developing appropriate evaluation strategies when comparing grid-cell values with point measurements and strategies for evaluating models using remote sensing scanning measurements (e.g.LIDARS, radars, SODARS, radar wind profilers).

11.3 Need for Numerical Experiments

In parallel to new theory developed for mesoscale modeling, additional numerical experiments will be needed to transfer current research to wind energy applications and to evaluate new theoretical relationships.

First, it is likely that many areas of new research already performed have not yet been incorporated into wind energy applications. The wind industry, for example, relies on surface wind fields predicted by current operational models, but vertical gradients in the wind fields could also be used to a greater extent. It has been noted that winds at turbine height are often estimated using observed or simulated winds that are then extrapolated using a power-law relationship. The power-law relationship is used despite the fact that it is known to be invalid under many atmospheric stability conditions. If mesoscale models produced accurate vertical wind shears, then this would be an opportunity to improve how models are used for wind energy applications. In this example, mesoscale models may be required to increase their near-surface vertical resolution to resolve wind shears for the wind energy industry. Cooperation among researchers, modelers, and wind energy personnel could generate recommendations on how to best run models, including such issues as model configuration (horizontal and vertical resolution), and which parameterizations are known to work best by the research community. Short-term benefits within a 1 – 2-year timeframe could be realized by establishing improved communication between the application and research communities.

Additonal activities are needed to benefit the wind industry over time. Developing new theoretical relationships described in the previous section will require additional analysis of existing measurements and additional longer-term measurements. These measurements are also needed by mesoscale models for evaluation purposes to quantify the uncertainty in the predicted near-surface vertical gradients in wind speed, direction, and turbulent properties associated with new parameterizations. Previous model evaluations have relied a great deal on field campaign measurements made over a short period of time (often less than a month) and at specific sites. However, evaluations of model parameterizations have shown that this strategy is not adequate for more generic model applications for all locations and time periods. Therefore, measurements at a variety of wind turbine sites over several years are needed to better assess the performance of current mesoscale model parameterizations and develop improved parameterizations based on new theoretical relationships.

It is important that these longer term measurements be part of a systematic strategy for evaluating mesoscale model forecasts for wind energy applications, which would be best accomplished by implementing a Developmental Testbed Center (DTC). Similar DTCs have been set up for specific applications such as hurricanes and precipitation forecasts [http:///www.dtcenter.org] to provide an objective means of assessing improved treatments for models. This DTC needs to be an on-going activity, similar to a long-term measurement program. The DTC methodology will also speed up transfer of knowledge from the research community to the application community, which is currently slow.

11.4 Potential Wind Energy Impact

Improved mesoscale models will lead to more accurate predictions of the 3-D variations in wind speed, direction, and turbulence. Better forecasts will subsequently improve turbine and plant design appropriate to realistic stresses, wind prospecting, and estimates of wind power to optimize wind resources for the nation's power grid.

The private sector currently does not have the resources or the capabilities to conduct a research program designed to improve mesoscale models. This role is more suited to government laboratory and university scientists, but such a research program will only succeed with close collaboration of the research and private sector.

The proposed research will also impact other disciplines that employ mesoscale modeling, such as atmospheric dispersion, air quality, climate change.

12. Create and Convene a Cooperative Working Group

12.1 Abstract

Create and convene a Cooperative Working Group of wind energy industry professionals and researchers, including the utility industry and atmospheric scientists, to define wind industry needs related to understanding wind energy resources, modeling capabilities, and ability to support those needs. A parallel task of this work group is to convey to the wind industry the current state of knowledge concerning mesoscale processes, atmospheric measurement capabilities, and mesoscale models and their applicability to wind energy. The objectives of this working group are two-fold:

1) Define in detail the data, modeling, and wind energy applications to be addressed by the other two research thrusts identified by the mesoscale working group: i) to establish and maintain a wind energy testbed, and, ii) to improve the atmospheric modeling capabilities of the wind industry.
2) Provide guidance to on-going research efforts related to wind resource characterization and provide a forum for exchange of ideas and sharing of results and data.

12.2 Problem or Opportunity

A significant gathering of wind energy professionals, researchers, and representatives from the meteorological community and industry met at the DOE SC-EERE Wind Resource Characterization workshop (January 14 – 16, 2008). The purpose was to understand the current state of understanding in wind resource characterization across a large range of applications in wind energy, from turbine-scale inflow characteristics and its impact on turbine dynamics to mesoscale modeling and climate implications, and to assess the research needs.

These two broad communities showed different cultural and operational backgrounds, vocabularies, and concepts of the essential ingredients for development and use of wind energy as a sustainable renewable national resource. The perspectives expressed by these two communities demonstrated diverse viewpoints, issues, concerns, and questions about science, economics, operations, and performance measures. It was evident from the discussions that there were inconsistencies of language, meaning, and priorities among the interested groups. For a successful national wind energy program, coordination of ideas, programs, resources, and development of a mutual understanding among the interested parties is essential so that common interests can be identified and addressed in a coordinated manner.

Of the four focus groups that were convened, one was devoted to mesoscale processes, with the specific intention of defining the most significant research needs pertaining to mesoscale processes and wind energy. It was clear over the three days of the Wind Resource Characterization workshop that there would be much overlap between the research needs identified by the four groups. It was also obvious that there is not yet a good understanding on the part of the wind industry as to the state of understanding of wind flow characteristics (i.e., the atmospheric boundary layer, in-flow turbulence, flow prediction in complex terrain or even relatively benign terrain) and the ability to predict wind flows reliably with mesoscale computer models. Likewise, there was not a good understanding on the part of the meteorological community of the information and understanding needed by the wind industry and researchers with regards to wind assessment, predicting wind power plant output, spatial and temporal variability of that output, and wind power forecasting. There was a sense, however, that given a coherent set of objectives, that the wind and meteorological communities could work towards transforming the current state of the art in mesoscale modeling into a tool better suited for wind energy. Thus, in order to bridge this gap in understanding, the first research thrust proposed by the mesoscale group was to create and convene a cooperative working group.

Reviewing the collected "problems or objectives" brought forward by the "Problem Definition Groups" that met during the first two days of the workshop, virtually all items identified fit into the following three broad categories:

1) Data needs – Data is needed to enable a better understanding of wind processes within the atmospheric boundary layer, in both benign and complex terrain, as well as under a variety of meteorological conditions (stable, unstable, prevailing winds, storm fronts, etc.). This data is also needed for initialization and validation of mesoscale models.
2) Model Development – Improved models, both physical and numerical, are needed for accurate wind prediction, especially as applied to wind energy. This includes predicting regional winds, understanding the PBL, and for wind power forecasting.
3) Application of atmospheric models for users – Forecasting, micro-siting, input to utility operators both operational and in understanding wind characteristics, for wind power developers, etc.

The Cooperative Working Group will benefit greatly from the recommendations of the several focus groups in forging a comprehensive approach to bridging the gaps between the constituencies. They may also benefit from a recent report [1] sponsored by the Office of the Federal Coordinator for Meteorology to address the atmospheric sciences capabilities to meet a variety of user needs related to atmospheric transport and diffusion of materials. The report provides recommendations for research and development. The microscale and macroscale atmospheric processes applicable to wind energy are at the same scales as the transport and diffusion processes and share deficiencies in modeling, data resources and scaling of results.

12.3 Potential Wind Energy Impact

The Cooperative Working Group will help bring some order to the broad range of issues confronting the wind power industry and foster cooperation with academia and industry to achieve a sustainable wind energy resource. It should bring understanding of the capabilities and limitations of the participants. More importantly, it begins the foundation of integrating the cultures, the research, the data, the measurement techniques, the environmental effects (wind on turbine(s) and turbines on local winds), the operational capabilities and needs of these two diverse communities. The working group can also serve an important role in facilitating communication of on-going research to all interested parties.

12.4 Key Events and Approximate Timing

The guiding principles of the Cooperative Working Group would be to begin prioritization of the workshop recommendations across all identified subject areas. Even though the full charter of the working group is not fully defined (that would be the job of the convening authority, likely DOE), implementation of the working group should proceed as soon as practical, with the purpose of addressing the two objectives:

1) Define in detail the data, modeling, and wind energy applications to be addressed by the other two research thrusts identified by the mesoscale working group: i) to establish and maintain a wind energy testbed, and, ii) to improve the atmospheric modeling capabilities of the wind industry.
2) Provide guidance to on-going research efforts related to wind resource characterization and provide a forum for exchange of ideas and sharing of results and data.

The fundamental goal here is to bring leadership – technical, administrative and operational - of the groups together to start! This may result in a large group, for many voices are to be heard. Convening this group in the near term may help DOE in defining its funding priorities in wind resource characterization, and in identifying other federal agencies that may also benefit from this work and may be interested in collaborating.

The working group should consider:

- Development of a charter and its working structure.
- Development of working reports of joint recommendations.
- Development of working papers on technical subjects to be shared with the represented communities through publications and seminars. (That is, seek feedback through presentations of technical material or concepts to the appropriate working level.)
- Development of workshops for specific issues.
- Report progress and obstacles to the convening authority quarterly, or more frequent if needed.

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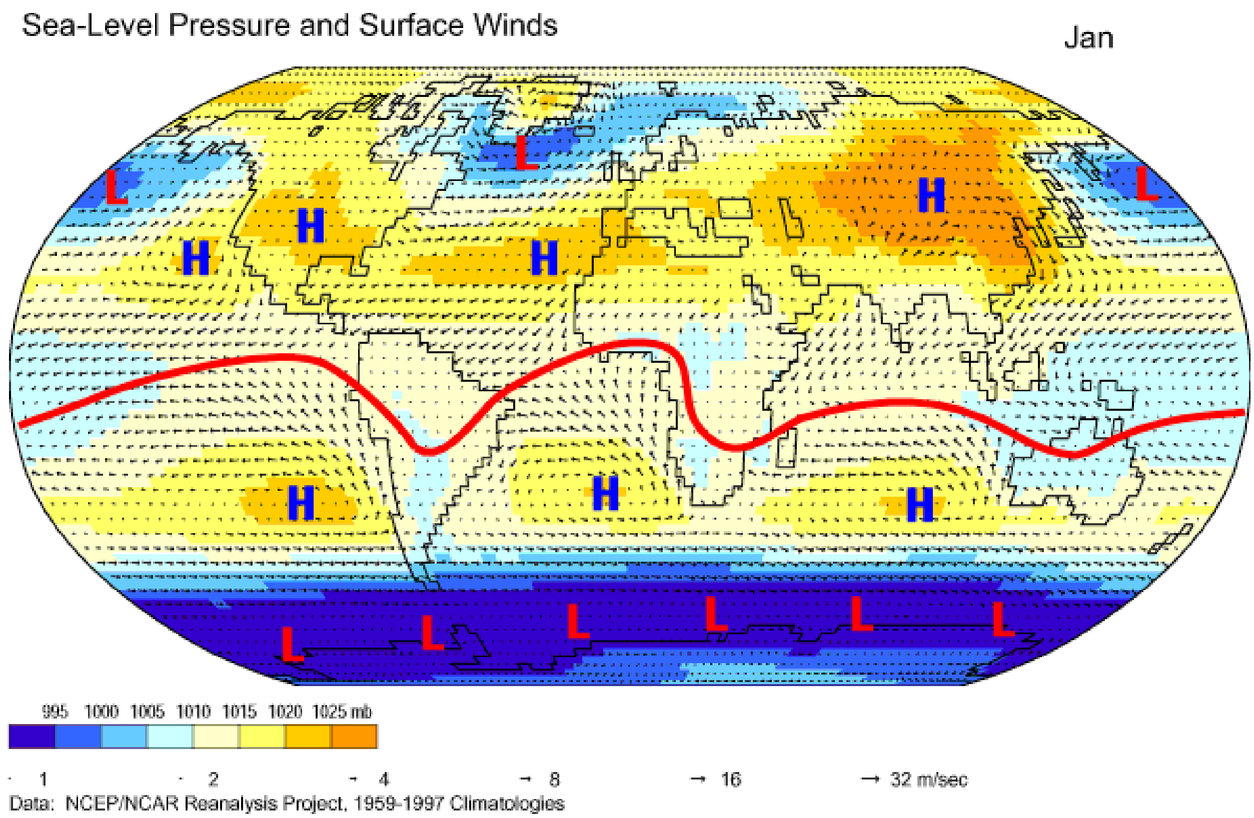
[1] OFCM, 2004. *Federal Research and Development Needs and priorities for Atmospheric Transport and Diffusion Modeling*. Report FCM-R23-2004, Washington, D.C.: Office of the Federal Coordinator for Meteorological Services and Supporting Research

Detailed Recommendations – Climate Effects



13. Improve Quantification and Identify Causes of Historical Change and Variability of Wind Resources

13.1 Problem or Opportunity

Climate variability and energy consumption are inextricably intertwined. For wind power applications, variations in weather and climate play a critical role in determining both short-term power production from a wind plant and accurate site assessments for long-term electricity generation. Thus, the robustness and representativeness of existing climate data sets for identifying past, current, and future trends, and variability in the potential wind resource are crucial to the ability of the nation to achieve the goal of producing 20% of electrical demand from wind power by the year 2030.

13.1.1 Inadequate data set inventory

A primary task under this research thrust is to supplement existing wind-power potential assessments and develop an enhanced (spatially explicit) inventory of the wind resource across North America via:

(i) Assessment and validation of existing observational data sets.
(ii) Assessment and validation of numerical model simulations.

Conducted with the following specific objectives:

(i) Quantification of current wind speed and energy climates.
(ii) Quantification of past variability and trends in wind speed and energy climates.
(iii) Attribution of causality to historical trends and changes in; the mean, variability of wind speed climates (including extreme winds).

Most current regional wind climatologies for the United States are based on interpolation of network surface station data presented in terms of wind atlases (e.g., Elliot et al, 1986), or developed from prognostic and diagnostic models using climatological compositing (Barthelmie et al, 2007). For site or local wind climates a range of techniques have been developed to extrapolate from short-term wind speed records to develop climatologically representative wind resource estimates. The most commonly applied include application of the WAsP model and measure-correlate predict both of which require long-term observations as input, and are critically dependent on the quality of those data.

Since the comprehensive wind resource (Elliot et al, 1986) study, more networks of observing stations making wind measurements have been deployed or enhanced. The resulting measurements include:

(i) Hourly wind speed and direction at 10 m from the ASOS/AWOS (Automated Surface/Weather Observation System, the majority of which were deployed in the 1990's) at nearly 1300 stations in the coterminous United States.
(ii) Twice daily wind profiles throughout the troposphere at over 70 rawinsonde stations.
(iii) Wind profiles in the near-surface layer (and above) from dozens of wind profilers.

(iv) Hourly wind speed and direction observations over surrounding waters (and the Great Lakes, though those platforms are removed from operation during the winter) at heights of 2 – 10 m above sea level.
(v) Ancillary data from NOAA's Real-time Observation Monitor and Analysis Network (ROMAN) and the more than 2200 interagency surface Remote Automated Weather Stations (RAWS) located throughout the United States.
(vi) Tower and other measurements from Ameriflux and Long Term Ecological Research LTER networks

In addition, there are a plethora of private observing networks such as is available from commercial entities (e.g., Weatherbug). Importantly, some of these networks also report parameters critical to determining stability and turbulence characteristics. Other potential archives of wind resource assessment data include those from power plant permitting processes, nuclear power plant monitoring, and state and federal air quality monitoring networks (e.g., the Environmental Protection Agency's "AirData" site at http://www.epa.gov/air/data/).

One problem inherent in long-term surface wind speed and direction data sets is the influence of changing characteristics of instrumentation, station location, and surrounding land use on the resulting observations. Hence, once possible data sources have been identified, there is a need to collate the data along with information regarding station histories, instrumentation, and quality-control methodologies, and to use statistical tools in conjunction with numerical modeling approaches to define the temporal and spatial representativeness. Some initial approaches to this issue are documented in Elliot et al (1986) and Pryor et al, (2007).

13.1.2 Inadequate long-term data and metadata

The quality of station histories varies greatly among existing data sets (for example, those mentioned in "Inadequate data set inventory" above), and is not necessarily complete. Although atmospheric measurements and modeling techniques have significantly advanced in recent years to provide a richer basis of information for estimating wind resources, data quality assurance remains paramount. In particular, two components of specifying wind resources are crucial: spatial and temporal coverage.

Spatial and temporal coverage. The ASOS/AWOS network is probably the most relevant source of approximately decade-long wind speed data in the United States, but its spatial coverage and terrain representativeness is dictated by aviation requirements; hence, most stations are located in valleys or relatively low terrain. Additionally, the data record from the ASOS stations is extremely limited in a climatological context (i.e., only approximately one decade of data are available for most stations). Longer data records are available from the National Climatic Data Center (NCDC) are subject to changes in recording protocols and instrumentation.

Assessment of offshore winds is severely limited by the scarcity of observations over the ocean. Although remote sensing platforms on satellites offer invaluable information on the surface winds over the ocean, they have limitations in the coastal zone due to contamination of the ocean pixels with land, obscuration by clouds, and coarse spatial (~ 12 – 25 km) and temporal (once or twice per day) resolution. New remote sensing technologies (for example, Synthetic Aperture Radar) provide highly spatially resolved wind speeds (and are cloud penetrating) (Hasager et al,

2005) and, although certain constraints limit verbatim use of the data (Pryor et al, 2004), they should be included in the aforementioned data archiving efforts.

In both cases – over the land and the ocean – there is need to integrate measurements and models to provide gridded coverage of meteorological parameters including the winds. Key among readily available model output are:

(i) Reanalysis fields of 10-m wind speeds created by the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) on global scale are available from 1948 to the present, but with a coarse resolution of 2.5° x 2.5° (Kalnay et al, 2001).

(ii) Reanalysis fields of 10-m wind speeds created by European Centre for Medium-Range Weather Forecasts (ECMWF) on global scale are available for a shorter-period (ending in 2002) then NCEP/NCAR and again at low resolution (Uppala et al, 2005).

(iii) The North American Regional Reanalysis of 10-m wind speeds created by the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) for north America (at a resolution of 0.5° × 0.5°)

Such data sets will be critical in providing a climatological context for short-term wind speed observational records.

Future modeling efforts that may contribute to such endeavors include the following projects. In FY07, NOAA began a project that provides new resources to support NOAA's climate reanalysis efforts. The project will support a variety of reanalysis activities including data set development, historical reanalysis efforts for a number of time periods, and data archive and delivery to the scientific community. The first task will be for 1979 and will present global reanalysis and re-forecast by the National Centers for Environmental Prediction, Climate Forecast System. NOAA recently held a Town Hall Meeting at the AMS Annual Meeting in New Orleans to discuss NOAA Reanalysis user needs. Some of the new efforts to provide high spatial resolution are illustrated by the NOAA's Rapid Update Cycle (RUC) system used mainly for weather forecasting. The RUC system assimilates all available data including sub-synoptic measurements of opportunity such as remote sensing, special stations, towers, etc. This system provides gridded meteorology on resolutions of 10 – 20 km over the continental United States.

Extreme Events. To quantify extreme wind speeds that are relevant for wind energy applications data (e.g., 50-year return period wind speeds), model formulation and quality, and climatological representativeness become ever more important (and demanding) issues. Additional related issues pertain to uncertainties in characterizing inherently rare events and the appropriate statistics to apply to wind climate metrics (Brabson & Palutikof, 2000).

Finally, to ensure full and accurate use of data derived from field programs, an infrastructure must be established for processing, quality control, archiving, and dissemination of data. Special attention should be paid to establishing standards for metadata, and standard formatting conventions (e.g., NetCDF) should be used. An archive similar to that developed by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for the Fourth Assessment Report of the IPCC might provide a useful model.

13.1.3 Incomplete understanding of discrepancies in historical trends derived from different data sets

Traditionally, wind resource site assessment has relied upon historical data. In a climatological context with a stationary climate, it is often assumed that a 30-year observational time series is adequate to characterize the mean wind speed and some characteristics of the probability distribution (e.g., the Webiull factors), plus intra- and inter-annual variability with a relatively high degree of confidence. Hence, it has to-date been deemed best practice to use resource characterization based on historical data to map likely current and future resources. There is some evidence that wind climates are evolving as a consequence of global climate change, but further analyses and integration of model simulations is warranted.

Recent work (Pryor et al, 2007; Freedman et al, 2008) has shown that the ability to detect wind speed trends is even more of a challenge than other climate variables, such as temperature or precipitation. Further, disparate trends have been determined using differing reanalysis data sets and/or reanalysis data relative to in situ observations (Pryor et al, 2006a) (Pryor et al, 2008). Reconciling these differences and determining whether trends in wind speed are the result of natural fluctuations (both periodic and aperiodic), a consequence of long-term trends related to global climate change, or a combination of both remains uncertain.

Downscaling studies of past and possible future climates are relatively sparse (and principally focused on Europe (e.g., Pryor et al, 2005a, Pryor et al, 2005b, 2006b). In addition, further application of tools designed to generate regional/local climate realizations from downscaling of global climate models (e.g., Regional Climate Models and empirical downscaling models) to both historical and prognostic periods will help in quantifying and assigning causality to changes in wind climates.

It is crucial that the quality, spatial, and temporal characteristics of all existing wind resource data sets be critically inventoried and inadequacies characterized for improving research into past climate, use in evaluation and validation of climate models, and identification of observational weaknesses.

13.1.4 Need to quantify explanatory power of regional/global forcings of wind climates across a range of scales

Accurate estimates of the local wind resource and effects upon turbine performance are dependent upon atmospheric and land-surface forcings across a spectrum of scales – from the synoptic (thousands of km^2), through the mesoscale (tens to hundreds of km^2), down to local (km^2 or less), and even micro scales (mm^2). A thorough understanding of how this energy cascade affects resource assessment and estimated wind power production is needed. Currently, these assessments are done on a site-by-site basis, using a potpourri of existing station data and limited on-site monitoring data, together with tools described in brief above, to estimate annual and seasonal scaled up wind speeds, speed shears, icing losses, and return periods for extreme events — all necessary to estimate long-term energy production at sites ranging from simple to complex terrain. Given that a 1% error in wind speed estimates for a 100-MW wind generation facility can lead to losses approaching $12,000,000 over the lifetime of that plant, a better understanding of the physical and dynamic processes across the range of scales that create a particular wind climate is needed.

13.2 Needs from Computation/Theory

General circulation models (GCM) used for climate simulations are not useful for direct simulation of near-surface wind speeds (Pryor et al, 2006b), however, they are critical tools for understanding the climate system under an evolving atmospheric composition and they are increasingly skillful in simulating many of the features of the global climate (IPCC, 2007). Both GCM and regional climate models (RCMs) exhibit some weaknesses in determining the accuracy of atmosphere-surface exchange and energy partitioning at the surface that critically determine the simulation of the atmospheric boundary layer (ABL) (Emmanuel, 1994; Garratt 1992). However, such models are a critical component of efforts to consistently simulate wind climates and energy resources across large spatial scales and to develop physically consistent linkages to aspects of the global climate system. Research undertaken to date implies regional climate simulations of wind climates are strongly dependent on the GCM used to provide lateral boundary conditions for RCM (Pryor et al, 2005a), but few such comprehensive studies have been conducted over the United States, although preliminary efforts are being conducted in conjunction with the North American Regional Climate Change Assessment Program (NARCCAP). Such efforts would be enhanced by implementation of innovative statistics (e.g., Baysian ensembling) and development of enhanced metrics of model skill.

With large-scale penetration of wind energy into the electricity generation network, there is also a need to better understand the spatial and temporal scales on which wind exhibits coherent behavior. Such research can be conducted using RCM and reanalysis products in addition to observational records to determine an optimal geographic dispersion of wind plant developments (Pryor et al, 2006a) to ensure fluctuations in power production are minimized and can accommodated in the system without the need for excessive spinning reserve.

As described above for local assessment of wind resources, RCM and reanalysis products can be used to provide lateral boundary conditions for mesoscale models (e.g., MM5) and at higher resolution, LES can be conducted for case-study simulations. Present ABL parameterizations in GCM/RCM and mesoscale models use a variety of closure schemes, incorporating Monin–Obukov similarity relationships. First order (ensemble or K-theory) works fairly well for the surface ("constant flux") layer, but fails in turbulent flows dominated by large eddies (e.g., in the convective ABL). Higher (one-and-a-half, second order) closure schemes are also used with varying success. In LES, the large-scale motions of the flow are calculated, while the effect of the smaller universal scales—the so called sub-grid scales—are modeled using sub-grid scale parameterizations. As discussed by the mesoscale scale modeling group, there is an important discontinuity at 100 m to 1 km between modeling at the mesoscale and using LES. This is an important scale that needs to be explicitly resolved (or at least sufficiently parameterized) in order to facilitate modeling for wind resource assessment purposes.

13.3 Needs from Observations/Experiments

As articulated above, key aspects of the needs within this recommendation are:

(i) Creation of an inventory of quality controlled data sets for wind energy applications. These observations exist and hence the major need is to evaluate the data, generate high-quality data products and facilitate access to those data.
(ii) Since much of these data are available only very close to the Earth's surface (i.e., at 10 m), they are not directly pertinent to determining the wind energy resource at typical turbine hub heights (currently 70 m, but increasing). Such efforts should include development of information on actual vertical profiles of winds and turbulence. A key component of future field projects should be the development of partnerships between those involved in research in the private sector and in government and academia. Key resources in such measurement campaigns include: meteorological towers, tethered balloons, aircraft studies, and remote sensing platforms including acoustic sounders, wind profilers, and LIDARS.
(iii) Both (i) and (ii) also need to address issues related to extreme events (wind speed, vertical speed and direction shear, temperature, and icing) that affect turbine operations. Maximum winds and gustiness is frequently missing or limited because of coarse time intervals. Efforts should be directed to investigate optimum sampling intervals that are relevant to turbine operations and define their statistical and dynamical distributions. Further comprehensive evaluations of applications of statistical methods for wind extremes should be undertaken.
(iv) The majority of the tools developed and applied to climate analysis to establish model skill have not focused on wind climates, hence additional technique development may be necessary.

13.4 Potential Wind Energy Impact

The proposed research articulated herein will provide:

- Increased confidence in resource estimation for future planning and validation.
- Improved understanding of physical mechanisms responsible for trends and variability for wind resource assessment.
- Facilitate future model development for enhanced estimation of the wind energy resource and variability of that resource.
- Reduced risk/uncertainty for financial investment in wind plants and improved warranty terms.

13.5 Key Events and Approximate Timing

For the modeling aspect of this research thrust, the following needs (and proposed timelines) have been identified:

1. Assess the strengths and weaknesses of current generation models (global/regional/local) to reproduce the trends and variability (timeframe = 3 yrs).
2. Develop metrics for model evaluations (timeframe = 1 yr).
3. Develop a coordinated set of model experiments to understand wind resources, trends and variability (timeframe = 3 – 5 yrs).
4. Quantify the scales of coherent variability of wind speeds (both temporal and spatial) and links to global and regional forcings (timeframe = 1– 3 yrs).

For the observational aspect of this research thrust, overarching goals and timelines include:

1. Create an inventory of quality controlled data sets for wind energy applications (timeframe = 1 – 2 yrs).
2. Develop techniques to analyze data sets for wind resources (timeframe = 1 yr).
3. Produce comprehensive evaluations of applications of statistical methods for wind extremes (timeframe = 2 – 3 yrs).

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14. Improved Quantification of Future Changes in the Mean and Variability of Wind Climates/Resources

14.1 Problem or Opportunity

Wind resources are strongly dependent on climate, which varies on a wide range of temporal and spatial scales. In the free troposphere, winds are determined by large-scale pressure gradients that are forced by the thermal contrasts between continents and oceans, and mountains and valleys. Within the PBL, small-scale turbulent motions are induced by flow over terrain features. Hence, large-scale circulation and local or regional scale terrain features are two important factors that determine wind climates.

A robust large-scale feature simulated by global climate models for the future is the northward shift of storm tracks and expansion of the subtropical high in the mid-latitudes (IPCC 2007), which are related to changes in the north-south thermal gradient and stability of the jet stream as the polar region warms up more than the lower latitudes under greenhouse warming. Such changes in the large-scale circulation and their interactions with the terrain could have significant impacts on wind patterns in the United States. At the regional scale, wind resources could also be influenced by changes in land use and other anthropogenic factors that alter the spatial distribution of heating and atmospheric stability.

There is an urgent need from industrial and developmental perspective for future wind resource projections to assess the viability of existing wind plants and planned future wind plants. However, no cohesive assessment of possible future wind climates is currently available for the United States to provide the information needed for future planning of wind resources.

14.1.1 Assessment of future wind climates

Coupled Atmosphere-Ocean General Circulation Models (AOGCM) are critical (and increasingly skillful) tools for assessing future climate states (IPCC, 2007), but operating on spatial scales on the orders of hundreds of kilometers in the horizontal and very low resolution in the vertical, they are incompatible with the needs for assessing regional and local wind climates, and exhibit low skill in reproducing historical wind speeds (Pryor et al, 2006). Hence, it is necessary to employ downscaling techniques for generation of higher spatial resolution climate parameters. These studies may employ:

- Physical/dynamical methods, where a Regional Climate Model (RCM) or high resolution or variable resolution atmospheric GCMs are used to produce finer resolution fields (e.g., 10 – 50 km) of the parameter of interest in the study region from the large scale description of climate produced by AOGCM (Giorgi and Mearns, 1999; Leung et al, 2003 and 2006).
- Statistical/empirical methods, where a transfer function (or functions) is developed that statistically relates the large scale climate parameters generated by the AOGCM to the near-surface parameter of interest (Pfizenmayer and von Storch, 2001; Katz et al, 2002).
- Or a hybrid combination of the above two methods.

Additional operational tools are emerging for seasonal type climate forecasts (9 months) that should be examined and tested for prediction of short climate trends (Saha et al, 2006). This type of forecast predicts winds at 10 m and 850 mb that can be used for the analysis of seasonal variability.

Although many studies have evaluated downscaling and seasonal forecast techniques for hydrologic and thermal parameters (e.g., Anderson et al, 2003; Leung et al, 2004), very few have analyzed them in terms of their skill relative to wind climates. The latter includes studies over northern Europe (Pryor et al, 2005a; Pryor et al, 2005b, c, 2006) and in the United States (Conil and Hall, 2006; Elguindi and Giorgi, 2005; Gustafson and Leung, 2007) to evaluate the downscaled winds when the large-scale circulation is provided by AOGCMs or global reanalysis. These studies have identified strengths and weaknesses of current downscaling techniques in capturing the large spectrum of wind variability.

Besides reconciling the spatial scales between global models and wind resources, there is also a need to reconcile the temporal windows to better coincide with the needs of the wind energy industry – i.e. climate impact studies are typically performed to assess changes 30 – 50 years into the future in order to differentiate the climate change signal from inter-annual variability (or noise), while the industry need is focused on the planning horizon of 10 – 30 years. The climate community is beginning to tackle decadal climate prediction (Smith et al, 2007), so much research is needed to combine and exploit both knowledge of the initial land and ocean states and sensitivity to external forcings.

Facing the challenge of scale reconciliation, research must be performed to refine downscaling techniques to quantify and reduce the sources of model errors. A comprehensive study to evaluate and inter-compare climate model projections of winds and wind extremes would have significant value for wind resources planning. The study should be complemented by the hind-cast evaluation of the climate models using available climate data including satellites to determine the model skill in capturing historical variability in wind climates. This inter-comparison would provide guidance on confidence levels in resource estimation for future planning and validation.

14.1.2 Comprehensive measurements of wind climates and resources

To assess trends in wind climates, it is crucial to develop a plan for long-term observations of the boundary layer parameters including winds and turbulence. The observations should be spatially and temporarily representative with an emphasis on measurements above the usual 10-m heights. Although some studies have attempted to analyze data from heights relevant to wind turbines that have hub-heights of 50 –100 m, these are usually limited in terms of the duration of record (Archer and Jacobson, 2005) and/or geographic coverage (Klink, 2007).

Another area that is extremely important to pursue is turbulence measurements aloft for long-term monitoring as well as comparison of standard and sonic anemometers for wind statistics (Koracin et al, 2007). A consensus on defining important turbulence descriptors and their sampling and averaging time needs to be reached by research and application entities as well as utilities and wind and turbine developers.

The use of satellite and other ground-based remote sensing for wind resource assessment should be further evaluated and standard methods should be designed to provide high horizontal and vertical resolution of the wind fields (Barthelmie et al, 2003; Barthelmie et al, 2006; Hasager et al, 2006; Hasager et al, 2005). Satellite borne sensors such as QuikSCAT (Chelton and Freilich, 2005; Sampe and Xie, 2007) and SAR are key components of this capability. However, the former satellite has been operational for the last seven years, and unfortunately, there are no firm commitments for extending its operational mission for the future.

Thus, in brief, a number of challenges arise when we begin to connect future climate considerations with what is necessary for planning today. These challenges include:

- Incomplete development and evaluation of downscaling tools used to simulate wind climates, including the extremes.
- No coordinated effort to develop and inter-compare future wind climate projections, quantify sources of error, and assess uncertainties.
- A disconnect between industry transmission planning which looks ahead at the 10 – 30 year planning horizons and challenges in decadal climate prediction.
- Limited long-term data sets and monitoring of wind resources in both a historical and future climate context.
- Lack of efforts to combine ground-based and remotely sensed information.

14.2 Needs from Computation/Theory

Consistent with the other recommendations for this topical area, improved and new techniques for scale reconciliation in both time and geographic (i.e., downscaling) coverage is essential to connect climate considerations to management of variability of wind resources. Utilizing existing models and archived global climate simulations, we can begin to examine projected changes in winds, determine any robust signals across the multiple scenarios, and relate the changes to thermal and dynamical changes in circulation regimes. A coordinated effort should be organized to develop and compare multiple downscaled future projections of winds for the United States to enable more detailed analysis of wind changes at the regional scale in response to large-scale circulation changes as well as changes that result from interactions between large-scale changes and terrain features and changes in regional forcings such as land use. Comparison between global and regional simulations, as well as across different downscaling techniques should be performed. These efforts will identify the largest sources of uncertainty in projecting future wind climates to enable more focused research to better characterize and reduce uncertainty.

In addition, by combining existing models and historical data sets, we can immediately begin to examine the relationships between extreme winds and the large-scale and mesoscale circulation (e.g., interdependencies between winds, temperature, and moisture) to provide a useful framework to understand extreme winds in the historical records. This framework can be applied to existing and new AOGCM and downscaled simulations to assess the nature and likelihood of extreme wind changes in the future.

14.3 Needs from Observations/Experiments

High-fidelity observational data are necessary to quantify and validate wind resources and to support long-term, trend analyses and modeling for the purposes of quantifying future climate change impacts. Leveraging state and DOE efforts (e.g., DOE Tall Tower facilities), there is a need to continue robust measurement programs to quantify future trends, especially focused at the wind turbine operational levels (ground to 300 m) accounting for wind shear and boundary-layer interactions. Providing necessary data to fill the interface between global, regional, and local mesoscale models is critical as these interfaces often provide the highest degree of modeling challenge. Remotely sensed data from satellites and ground-based platforms, as well as continued development of techniques/instrumentation need to be supported. Highly instrumented locations near appropriate wind resource-quality sites need to be linked with the climate modeling efforts to enable the link between climate impacts to energy planning needs. Promising research areas and topics are as follows:

Winds from the surface to above the rotor plane--the Atmospheric Boundary Layer (ABL). The rapid development of turbine technology and accompanying rise in with hub heights imposes the need for estimating winds in the range up to 100 - 200 m and above. This necessitates the incorporation of existing knowledge of the ABL and development of new techniques for observations and modeling of turbine interaction with the boundary layer. Additionally, the atmosphere beyond these heights needs further study to understand the possible influence of phenomena such as low-level jets, vortices, and wind rotors. The main information sources are meteorological towers, tethered balloons, aircraft studies, and remote sensing platforms including acoustic sounders, wind profilers, and LIDARS.

Ground-based remote sensing (GBRS): including but not limited to SODAR, LIDAR, RASS, MAPR, and NEXRAD. These measurements have traditionally focused on the study and observations of small- and mesoscale flow patterns. Turbulence parameters, for purposes of wind resource assessment, require long-period estimates both near the surface and aloft as they make a significant impact on turbine operations and the life-time of turbine components. However, there is little knowledge of what turbulence parameters (that is, the components of the Reynolds' stresses) are of most interest, besides turbulence intensity. A consensus on sampling and averaging intervals should be reached since raw turbulence data are not necessarily archived. Detection of turbulence by remote sensing should be calibrated, evaluated, and compared to tower-based turbulence measurements. Standardized sampling, averaging, and evaluations should lead to a protocol for turbulence measurements of interests for wind resource assessment.

Extreme events. There is no firm guidance how extreme events (wind speed, vertical speed and direction shear, temperature, icing) affect turbine operations. Maximum winds and gustiness is frequently missing or limited because of coarse time intervals. Efforts should be directed to investigate optimum sampling intervals that are relevant to turbine operations and define their statistical and dynamical distributions. Climate periods of at least 20 – 50 years should be considered.

Measurements over the ocean. There are only sparse observations and short-term (~ 20 years or less) data sets currently available. Satellite remote sensing is, by practicality, the only solution for comprehensive measurements over the ocean. However, these measurements are spatially and temporally constrained. Thus, there is a need for increased resolution of the satellite-borne instruments, new retrieval algorithms, and data validation through surface observations.

Additionally, it may be desirable to develop a permanent test bed and field observation facility focused on wind resource assessment, similar to the Atmospheric Radiation Measurement (ARM) Program sponsored by DOE. Further, shorter-term field projects should be deployed at existing wind plants in a variety of terrain (simple, complex, marine) to capture the spectrum of ABL characteristics, including feedbacks between the physical structure of the wind plant and its surrounding environment. With added instrumentations related to wind, the ARM Mobile Facility (AMF) can be a significant resource for this purpose.

14.4 Potential Wind Energy Impact

The proposed research articulated herein will provide:

- Increased confidence in resource estimation for future planning and validation.
- Improved understanding of physical mechanisms responsible for trends and variability for wind resource assessment.
- Continued improvement of modeling capabilities and statistical analysis tools.
- Facilitate future model development for enhanced estimation of the wind energy resource and variability of that resource.
- Reduced risk and uncertainty for financial investment in wind plants and improved warranty terms.
- Payoffs in assessment of other climate change impacts (e.g., improvement in estimates of evapo-transpiration or air pollution forecasts).
- Recommendations with regard to wind plant design and planning within the context of climate change.

14.5 Key Events and Approximate Timing

The following needs from computation and theory (and proposed timeframes) have been identified:

- Refine or develop new techniques for scale reconciliation (downscaling) (timeframe = 3 – 5 yrs).
- Perform multiple global and regional model simulations for evaluation of existing downscaling techniques and to facilitate technique inter-comparisons (timeframe = 3 – 5 yrs, continuous).
- Develop certainty/uncertainty quantification and assess major sources of uncertainty (in this case e.g. model divergence, but also strongly linked to recommendation 1) (timeframe = 3 – 5 yrs).
- Archive appropriate parameters/time scales from AOGCM (it may be necessary to request additional model simulations) (timeframe = 3 – 5 yrs, linked to IPCC cycle).
- Examine probability of changes in extreme events relevant to wind energy (timeframe = start immediately but 5+ yrs for reaching high level of skill).

Overarching goals and timelines of the experimental component of this thrust are:

- Develop a long-term, robust measurement (e.g. wind shear) program to quantify future trends (especially boundary-layer observations - i.e. above 10 m - similar to LTER). Precise variables to be based on data analysis conducted in recommendation 1. (ongoing, annual review).
- Strong need for continued and continuous remote sensing data from satellites and ground-based platforms and for continued technique/instrument development (ongoing, annual review).

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15. Interactions Between Wind Plants and Local, Regional, and Global Climates

15.1 Problem or Opportunity

Wind plants extract momentum from the free atmosphere from their turbine positions in the lower part of the ABL. The ABL depth changes with time of day and time of year. In the warm season the daytime boundary layer grows rapidly in early morning to a daytime maximum depth generally in mid-afternoon that may be of order 10 – 20 times the hub height of currently used turbines. With diminished surface heating in the late afternoon, large-scale turbulent eddies in the ABL gradually diminish in strength, thereby decoupling the surface flow from the free atmosphere. This allows for slow growth of the surface-based nocturnal boundary layer, which is much less deep and by sunrise, may have maximum depth of the order of the hub height of turbines. The cold season ABL diurnal cycle follows a similar development, although its maximum daytime depth is usually much lower due to reduced surface-sensible heat flux compared to the warm season. Of course, cloudiness, large-scale baroclinicity, and passing synoptic-scale weather systems can create large departures of ABL behavior from this highly idealized picture.

Impacts of wind plants on local and regional meteorological conditions span influences at the microscale, as represented by surface-sensible and latent heat flux, to the regional scale where these microscale changes aggregate to influence convergence/divergence patterns, low-level moistening and heating, and ultimately precipitation processes. The potential impacts of continental-scale wind power are global in extent (Kirk-Davidoff and Keith, 2008). Between these spatial extremes are influences on turbulent dispersion and interactions with other local scale factors such as urban influences, non-classical mesoscale circulations, sea-breezes, and mountain-valley circulations, etc. Land use in the environmental “influence-footprint” of wind plants may include natural ecosystems in complex terrain and coastal areas, low-density residential and commercial, grazing, and intensive-cropping agriculture. Changes in surface sensible and latent heat exchanges can have significant economic impacts, particularly for example with regions of intensive agriculture where changes in surface wind, dew-deposition periods, daily max and min temperatures, spray and pollen dispersing potential, insect populations (both pests and pollinators) due to wind plants may affect landowner income derived from non-wind power sources. Not all impacts of wind plants will be bad. For example, they may provide some protection from frost occurrences in some regions where frost-sensitive crops are grown.

Lacking long-term observations of wind speeds in and around wind plants, we can only speculate on how collections of wind turbines interact with this diurnally and seasonally varying flow. The layer of momentum extraction defined by the maximum and minimum turbine blade elevations will be coupled to overlying and underlying layers through turbulent processes that depend on diurnally varying and height-varying atmospheric stability. The scales of turbulence that vertically transmit the influence of momentum extraction in the turbine layer may exceed the blade diameter under strong convection, but surely will be much smaller than blade diameter under stably stratified conditions. Mechanical mixing by the turbulence kinetic energy (TKE) generated by the blades will alter the undisturbed stratification, particularly during the period from early evening to early morning when turbine-generated TKE will have space and time scales greater than those of the undisturbed ABL. Wind-plant induced changes in surface-layer sensible and latent heat exchange processes could be quite significant during this period, particularly in relatively flat rural areas where terrain or other surface inhomogeneities are not present to introduce larger scales of turbulence.

To understand long-term effects of wind plants will require better quantification of interactions between wind plants and the local/regional climate, and possibly some larger scale effects, rather than a case by case or general description. Yet, the lack of observations precludes substantial refinements to even a general description. Vertical profiles of mean and turbulent wind characteristics are urgently needed for better understanding both of conditions within the momentum extraction layer that influence power generated and blade/gearbox stresses, and of conditions above and below this layer to characterize the transmission of turbine influences both to the surface layer below and the free atmosphere above. Increases in greenhouse gas concentrations likely will decrease surface-layer stratification under undisturbed conditions, but the presence of a momentum-deficient layer aloft created by wind turbines surely will modify this situation. And global climate change will alter synoptic and mesoscale circulation patterns with yet-to-be-determined consequences on surface wind speeds.

15.2 Needs from Computation/Theory

The simplistic conceptual model presented in the previous section calls for more rigorous mathematical description and testing. Modeling studies of the large-scale impact of wind farms (Keith et al, 2004; Baidya et al, 2004; Rooijmans, 2004; Adams and Keith, 2007; Kirk-Davidoff and Keith, 2008; Barrie and Kirk-Davidoff, 2007) have used global and regional scale models such as CAM, WRF, RAMS, or MM5 with grid spacing as large as 250 km and as low as 1 km. These studies indicate that the existence of substantial remote impacts on climate depends strongly on the horizontal scale of the region over which momentum is extracted. Fast (2008) has identified the horizontal scale interval of 100 m to 1 km as the "no-mans land" between LES models and mesoscale models where much better understanding is needed of the momentum extraction process. This will require more detailed momentum extraction models (MEMs), such as described by Wang et al (2001) for flow through vegetation, that recognize the spatial placement of turbines and the spatial extent and details of how mean kinetic energy (MKE) is converted to TKE.

Moreover, rotational motions of blades will create a special class of motions that excite specific physical processes and scales of turbulence that must be simulated. Such models must then be inserted into conventional ABL models or LES models that link the free atmosphere to the surface [3 years for development, 5 years for evaluation]. Such ABL/LES/MEMs must further be coupled to conventional mesoscale weather models or regional climate models for assessing larger-scale impacts [5+ years]. Improved simulation and model verification at the regional scale will provide a basis for developing better mesoscale and LES parameterizations needed to better assess the global impact of wind plants through GCMs. It is expected that individually these component models will be highly computationally intensive. Simulations using fully coupled modeling systems across scale should take advantage of high performance computers to fully explore scale interactions and model coupling.

However, operational use of fully coupled modeling systems across scales is unrealistic for many practical purposes. This calls for continued development of “wind-plant parameterizations”, such as Adams and Keith (2007), which go beyond simple increases in mesoscale grid point surface roughness that can be used to represent the overall influences of such parks on surface and free-atmospheric conditions without excessive computational burden.

15.3 Needs from Observations/Experiments

Existing wind climatologies lack information on conditions at typical hub heights of modern turbines. The region of interest falls in a gap between surface and short tower measurements at the lower end and lowest level of radiosonde measurements at the upper end. Diurnal, seasonal and interannual patterns of mean and turbulent wind fields are needed as a baseline for establishing “undisturbed” conditions in the vicinity of wind plants. A systematic analysis of data from all available existing tall (>100 m) towers (even in regions not having or considered as highly desirable for wind-power development) is needed to improve understanding the climatology of conditions above the atmospheric surface layer. Special attention should be given to surface and radiosonde data concurrent with these hub-height data in order to develop parameterizations of conditions from the power-extraction region from more readily available data. Opportunities for using Aircraft Communications Addressing and Reporting System (ACARS) data also should be explored.

Observational facilities specifically devoted to assessing impact of wind plants on undisturbed boundary-layer flow are needed—ideally, one such facility in complex terrain and one in relatively flat terrain [start immediately, continue 5+ years]. Such facilities should consist of networks of meteorological towers of a height 1.5 times the hub height located upwind, downwind, and within the footprint of each wind plant. Measurements should include mean wind speed and direction, turbulence, temperature, and dew-point temperature at multiple levels within, above, and below the momentum extraction layer. Surface sensible and latent heat budgets also should be measured (i.e., soil moisture, soil temperature, and precipitation) as well as conditions aloft above the tower layer. Measurements of high frequency (~1 Hz) soil-surface pressure fluctuations induced by turbines would provide opportunities for documenting potential influences on mammal auditory function and “pressure-pumping” of water-vapor and other trace gases from sub-surface ecosystems (Takle et al, 2004). Multi-year measurement facilities and programs should be established to ensure full assessment of interannual variability.

Currently available remote-sensing technologies should be deployed at operational wind parks that also have *in-situ* observations for more full three-dimensional wind field [start immediately, continue 5+ years]. Wind profilers operating at 915 MHz have demonstrated success in observing ABL depth, wind speed, direction, and virtual temperature profiles (e.g., White, et al, 2007; Wilczak et al, 2007; MacDonald et al, 2007; Shaw et al, 2007). Satellites using synthetic aperture radar (SAR) have proven to be capable of observing the wakes of off-shore wind plants (Christiansen & Hasager, 2005). The ARM Mobile Facility (AMF) can play a central role in advancing the measurements in the vicinity of wind plants.

15.4 Potential Wind Energy Impact

The payoff of better understanding of interactions of turbine parks with the atmospheric boundary-layer includes better knowledge of influences on natural or managed land use of the landscape within and in the near vicinity of the wind park, better knowledge of possible regional influences on mesoscale meteorological systems beyond the immediate vicinity of the wind park, and better knowledge of how one wind plant might influence another nearby wind plant (particularly pertinent to off-shore wind plants). Better understanding of these environmental impacts will enable comparative analyses of the sustainability of alternative electrical generation sources. The potential of measurable environmental impact of wind plants brings potential legal exposure for negative impacts on adjacent land use. For instance, changes in daily maximum or minimum temperatures or evaporation and dew deposition in adjacent agricultural lands might influence pest or pathogen infestations or crop pollination success. Quantitative measurements and modeling would help establish limits on risk exposure and suggest possible advantages for alternative land use.

15.5 Key Problems and Opportunities

Arrangements should be made with wind plant operators to acquire data for use in these studies. Negotiations on data availability should be managed by DOE in conjunction with a third-party analysis team, such as from a university, to ensure that confidentiality on sensitive data is maintained. This will provide data on both basic meteorological conditions (see above list of variables and boundary-layer characteristics to be analyzed) and wind power production. Modeling studies also should be conducted, preferably with multiple models and coupled modeling systems, to assess the ability of models to capture mean and turbulence characteristics and extreme events. This would enable assessment of model ability to provide useful predictive capabilities for power generation planning and pre-emptive actions by wind plant operators, a prospect that should offer incentive for industry participation.

Understanding of boundary-layer conditions associated with power production (including conditions potentially hazardous to turbines) and environmental impacts of wind plants will enable studies of long-term wind power production by use of regional climate models. The forthcoming North American Regional Climate Change Assessment Program (NARCCAP, 2008) simulations will provide future scenario climates at regional scales for planning future wind plant development and energy production. The recent results of Pryor et al (2007) that noted substantial apparent declines in wind speeds over the United States, particularly the eastern half, over the period 1979 – 2004 need to be replicated with models as a basis for assessing potential changes in wind power potential with future climate change.

Spatial (both vertical and horizontal) and temporal scales of importance for measurement and modeling must be recognized, both in conjunction with measurements at wind plants and in with models' (both reanalysis models and regional climate models) abilities to assess boundary-layer conditions in the lowest 300 m. Statistical downscaling should be used in addition to dynamical downscaling for comparison with site-specific measurements. Existing ARM sites and Ameriflux towers offer opportunities for such comparisons in a variety of locations throughout the United States.

Finally, to ensure full and accurate use of data derived from field programs, an infrastructure must be established for processing, quality control, archive, and dissemination of data. Special attention should be paid to establishing standards for metadata, and standard formatting conventions (e.g., NetCDF) should be used.

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Appendices

Appendix A – Workshop Logistics

Workshop registrants totaled 125, with actual attendance exceeding 95 percent. To ensure productive discussions and cogent recommendations, invitees were carefully chosen from the atmospheric science and wind energy engineering communities, and then personally invited to attend the workshop. The workshop enjoyed vigorous participation from both industry and research laboratories. Approximately 30% of the participants represented turbine manufacturers, wind plant owners/operators, wind resource estimation industry, or utility participants. Researchers from universities and federal laboratories constituted 66% of the registrants. Of the federal laboratory researchers, DOE laboratories were well represented (31 of 52), with strong participation from abroad (7 of 52, coming from Denmark, Canada, and Spain), from NCAR (5 of 52), from NOAA (8 of 52), as well as one DOD participant. The remaining 4% of the attendees represented federal agencies at managerial levels.

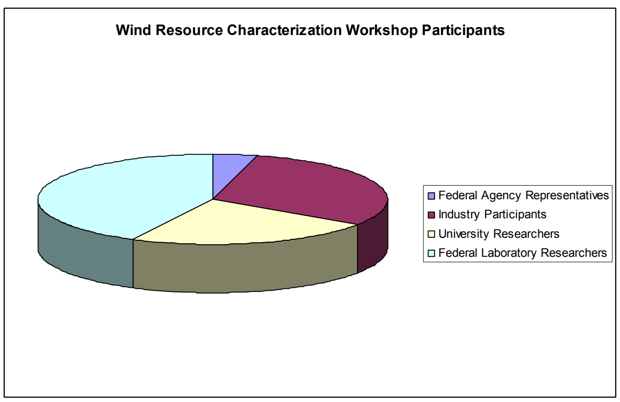

Figure 1: Breakdown of workshop registrants

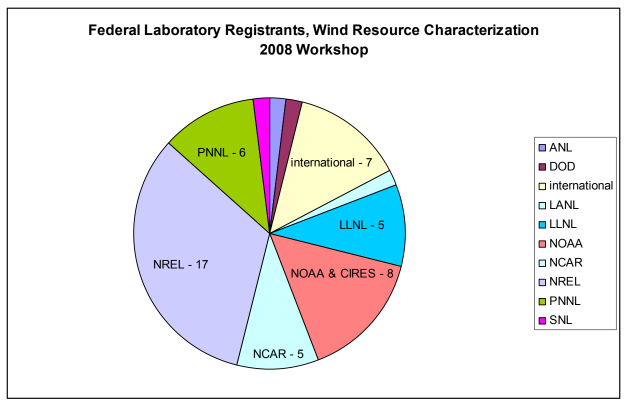

Figure 2: Breakdown of federal laboratory participants

Organization of the workshop promoted discussions of future research needs and methodologies across time and spatial scales, and between industry participants and members of the research community. The four focus areas of Turbine Dynamics, Micrositing and Array Effects, Mesoscale Processes, and Climate Effects anchored the discussions. These areas were introduced in four plenary presentations delivered by internationally recognized experts currently working in these fields. Participants then joined one of three "Problem Definition" breakout groups to address these focus areas. Each group consisted of about 40 people, and included participants from each community to promote knowledge exchange between the industry and the research communities. After the Problem Definition groups had addressed each of the four focus areas, participants then joined one of four "Recommendation" breakout groups aligned with their individual expertise to distill the problem definition discussions into a set of research thrust recommendations. Research thrust recommendations from each of the four groups were summarized in a plenary session at the conclusion of the workshop. Some of the thrusts were common to multiple recommendation groups.

Appendix B – Workshop Agenda

<table>
<tr><th colspan="14">Workshop on Research Needs for Wind Resource Characterization
14 - 16 January 2008
Omni Interlocken Hotel, Broomfield, Colorado</th></tr>
<tr><td rowspan="8">Monday</td><td>9:00 - 11:00</td><td colspan="12">Register and Prepare for Workshop</td></tr>
<tr><td>11:30 -1:00</td><td colspan="12">Lunch and Introduction</td></tr>
<tr><td>1:00 - 1:15</td><td colspan="12">OBER Workshop Goals and Welcome − Ashley Williamson</td></tr>
<tr><td>1:15 - 1:30</td><td colspan="12">EERE Workshop Goals and Welcome − Sam Baldwin</td></tr>
<tr><td>1:30 - 2:15</td><td colspan="12">Turbine Dynamics Plenary − Sandy Butterfield</td></tr>
<tr><td>2:15 - 3:00</td><td colspan="12">Micrositing and Array Effects Plenary − Jakob Mann</td></tr>
<tr><td>3:00 - 3:30</td><td colspan="12">Break</td></tr>
<tr><td>3:30 - 5:30</td><td colspan="4">Problem Definition Group A
(Chairs: S. Butterfield, R. Banta)

− Turbine Dynamics
− Micrositing & Array</td><td colspan="4">Problem Definition Group B
(Chairs: P. Veers, S. Zhong)

− Turbine Dynamics
− Micrositing & Array</td><td colspan="4">Problem Definition Group C
(Chairs: T. Mikkelsen, D. Lenschow)

− Turbine Dynamics
− Micrositing & Array</td></tr>
<tr><td rowspan="9">Tuesday</td><td>7:00 - 8:00</td><td colspan="12">Breakfast</td></tr>
<tr><td>8:00 - 8:45</td><td colspan="12">Mesoscale Processes Plenary − Jerome Fast</td></tr>
<tr><td>8:45 - 9:30</td><td colspan="12">Climate Effects Plenary − Katherine Klink</td></tr>
<tr><td>9:30 - 10:00</td><td colspan="12">Break</td></tr>
<tr><td>10:00 - 12:00</td><td colspan="4">Problem Definition Group A
(Continued)

− Mesoscale Processes
− Climate Effects</td><td colspan="4">Problem Definition Group B
(Continued)

− Mesoscale Processes
− Climate Effects</td><td colspan="4">Problem Definition Group C
(Continued)

− Mesoscale Processes
− Climate Effects</td></tr>
<tr><td>12:00 - 1:00</td><td colspan="12">Lunch</td></tr>
<tr><td>1:00 - 3:00</td><td colspan="3">Recommendation Group
Climate Effects
(R. Leung)</td><td colspan="3">Recommendation Group
Mesoscale Processes
(W. Bach)</td><td colspan="3">Recommendation Group
Micrositing & Array Effects
(P. Moriarty)</td><td colspan="3">Recommendation Group
Turbine Dynamics
(L. Carr, S. Schreck)</td></tr>
<tr><td>3:00 - 3:30</td><td colspan="12">Break</td></tr>
<tr><td>3:30 - 6:00</td><td colspan="3">Recommendation Group
Climate Effects
(Continued)</td><td colspan="3">Recommendation Group
Mesoscale Processes
(Continued)</td><td colspan="3">Recommendation Group
Micrositing & Array Effects
(Continued)</td><td colspan="3">Recommendation Group
Turbine Dynamics
(Continued)</td></tr>
<tr><td rowspan="9">Wednesday</td><td>7:30 - 8:30</td><td colspan="12">Breakfast</td></tr>
<tr><td>8:30 - 8:45</td><td colspan="12">Climate Effects Recommendations Plenary</td></tr>
<tr><td>8:45 - 9:00</td><td colspan="12">Mesoscale Processes Recommendations Plenary</td></tr>
<tr><td>9:00 - 9:30</td><td colspan="12">Micrositing & Array Effects Recommendations Plenary</td></tr>
<tr><td>9:30 - 10:00</td><td colspan="12">Turbine Dynamics Recommendations Plenary</td></tr>
<tr><td>10:00 - 10:30</td><td colspan="12">EERE Program Manager Remarks − Mike Robinson</td></tr>
<tr><td>10:30 - 11:00</td><td colspan="12">OBER Program Manager Remarks − Rick Petty</td></tr>
<tr><td>11:00 - 11:30</td><td colspan="12">Discussion and Closing Remarks</td></tr>
<tr><td>12:00</td><td colspan="12">All Depart</td></tr>
</table>

Appendix C – Workshop Attendee List

Tom Acker
Northern Arizona University
Email: tom.acker@nau.edu

Manda Adams
Institute for Sustainable Energy
Environment and Economy
University of Calgary
Email: manda.adams@ucalgary.ca

Chris Anderson
NOAA/ESRL/GSD
Email: sky.doc@gmail.com

Wayne Angevine
CIRES / NOAA ESRL
Email: wayne.m.angevine@noaa.gov

Walter Bach
Army Research Office
Email: bach@aro-emh1.army.mil

Mark Balas
ECE Department
Email: mbalas@uwyo.edu

Sam Baldwin
EERE/USDOE
Email: sam.baldwin@ee.doe.gov

Robert Banata
NOAA/ESRL - CSD3
Email: robert.banta@noaa.gov

Rebecca Barthelmie Barthelmie
Indiana University/Edinburgh University
Email: r.barthelmie@ed.ac.uk

Suresh Baskaran
Pacific Northwest National Laboratory
Email: suresh.baskaran@pnl.gov

Sukanta Basu
Texas Tech University
Email: sukanta.basu@ttu.edu

Larry Berg
Pacific Northwest National Lab
Email: larry.berg@pnl.gov

Kenny Braun
Vestas
Email: kebra@vestas.com

Kenneth Brentner
Penn State University
Email: ksbrentner@psu.edu

Ari Bronstein
DONG Energy
Email: ari.n.bronstein@gmail.com

Kevin Brundage
NOAA/GSD
Email: Kevin.Brundage@noaa.gov

Sandy Butterfield
NREL
Email: sandy_butterfield@nrel.gov

Daniel Cabezon
CENER
Email: dcabezon@cener.com

Lawrence Carr
Emeritus Scientist, US Army
Aeroflightdynamics Dir.
Email: lcarr@mail.arc.nasa.gov

Hung-Neng Chin
Lawrence Livermore National Laboratory
Email: chin2@llnl.gov

Robert Conzemius
WindLogics, Inc.
Email: bobc@windlogics.com

Dave Corbus
NREL
Email: david_corbus@nrel.gov

Richard Coulter
Argonne National laboratory
Email: rl_coulter@anl.gov

Jerry Crescenti
PPM Energy
Email: jerry.crescenti@ppmenergy.com

Ed DeMeo
Renewable Energy Consulting Services, Inc.
Email: edemeo@earthlink.net

Lori Diachin
LLNL
Email: diachin2@llnl.gov

Dennis Elliott
NREL/NWTC
Email: dennis_elliott@nrel.gov

Jerry Elwood
Department of Energy
Email: jerry.elwood@science.doe.gov

Peder Enevoldsen
Siemens Wind Power
Email: pe@siemens.com

Dariush Faghani
Helimax Energie inc. - GL Group
Email: faghanid@helimax.com

Jerome Fast
Pacific Northwest National Laboratory
Email: jerome.fast@pnl.gov

Evgeni Fedorovich
School of Meteorology, OU
Email: fedorovich@ou.edu

Lee Jay Fingersh
NREL
Email: lee_fingersh@nrel.gov

Frank Flottemesch
General Electric Wind Energy
Email: frank.flottemesch@ge.com

Sten Tronaes Frandsen
Risoe National Laboratory DTU
Email: sten.frandsen@risoe.dk

Jeff Freedman
AWS Truewind LLC
Email: jfreedman@awstruewind.com

Rod Frehlich
University of Colorado
Email: rgf@cires.colorado.edu

Bobi Garrett
NREL
Email: bobi_garrett@nrel.gov

Charlette Geffen
PNNL
Email: ca.geffen@pnl.gov

Al Germain
BP Alternative Energy - Wind
Email: al.germain@bp.com

Philippe Giguere
General Electric
Email: philippe.giguere@ge.com

Lucas Gomez
Iberdrola Renewable Eenergies
Email: lgomez@iberdrolausa.com

Bruce Green
NREL
Email: bruce_green@nrel.gov

Martin Greiner
Siemens AG
Email: martin.greiner@siemens.com

Scott Grindle
RES AMERICAS
Email: scott.grindle@res-americas.com

Maureen Hand
NREL
Email: maureen_hand@nrel.gov

Horia Hangan
Boundary Layer Wind Tunnel Laboratory
Email: hmh@blwtl.uwo.ca

Stephen Hannon
Lockheed Martin Coherent Technologies
Email: steve.hannon@lmco.com

Scott Haynes
PPM Energy
Email: scott.haynes@ppmenergy.com

Cheng-Hu Hu
Vestas Asia Pacific A/S
Email: chhhu@vestas.com

Kathryn Johnson
Colorado School of Mines
Email: kjohnson@mines.edu

Wesley Jones
NREL
Email: wesley_jones@nrel.gov

Bonnie Jonkman
National Renewable Energy Lab / National Wind Technology Center
Email: bonnie_jonkman@nrel.gov

Jason Jonkman
National Renewable Energy Laboratory
Email: jason_jonkman@nrel.gov

Gary Kanaby
Knight & Carver Wind Group
Email: gkanaby@knightandcarver.com

Neil Kelley
NREL/NWTC
Email: neil_kelley@nrel.gov

Katherine Klink
University of Minnesota
Email: klink@umn.edu

Eunmo Koo
Los Alamos National Laboratory
Email: koo_e@lanl.gov

Darko Koracin
Desert Research Institute
Email: darko.koracin@dri.edu

Leif Kristensen
Risoe National Laboratory/Technical University of Denmark
Email: leif.kristensen@tele2.dk

Don Lenschow
NCAR
Email: lenschow@ucar.edu

L. Ruby Leung
Pacific Northwest National Laboratory
Email: ruby.leung@pnl.gov

William Lindberg Lindberg
University of Wyoming
Email: lindberg@uwyo.edu

Steve Lindenberg
U.S. DOE Wind Program
Email: steve.lindenberg@ee.doe.gov

Julie Lundquist
Lawrence Livermore National Laboratory
Email: lundquist1@llnl.gov

David Malcolm
Global Energy Concepts, LLC
Email:
dmalcolm@globalenergyconcepts.com

Jakob Mann
Risø National Laboratory - DTU
Email: jakob.mann@risoe.dk

Lance Manuel
University of Texas at Austin
Email: lmanuel@mail.utexas.edu

Melinda Marquis
NOAA Earth System Research Laboratory
Email: melinda.marquis@noaa.gov

Jim McCaa
3TIER
Email: jmccaa@3tiergroup.com

Jon McGowan
University of Massachusetts
Email: jgmcgowa@ecs.umass.edu

Tony Meys
WindLogics
Email: tmeys@windlogics.com

Torben Mikkelsen
Risø National Laboratory, Denmark RISØ-DTU
Email: torben.mikkelsen@risoe.dk

Thomas Mills
Vestas Americas
Email: thmi@vestas.com

Jeffrey Mirocha
Lawrence Livermore National Laboratory
Email: mirocha2@llnl.gov

Soeren Mogensen
Vestas Asia Pacific, Wind & Site
Competence Center
Email: shm@vestas.com

Patrick Moriarty
NREL
Email: patrick_moriarty@nrel.gov

Philip Morris
Penn State University
Email: pjmaer@engr.psu.edu

Walt Musial
NREL
Email: walter_musial@nrel.gov

Dora Nakafuji
Lawrence Livermore National Laboratory
Email: nakafuji2@llnl.gov

Jonathan Naughton
University of Wyoming
Email: naughton@uwyo.edu

Andrew Oliver
RES Americas Inc
Email: andrew.oliver@res-americas.com

Joe Olson
NOAA-ESRL
Email: joe.ols@gmail.com

Lucille Olszewski
CH2M HILL
Email: lucille.olszewski@ch2m.com

Andy Paliszewski
Siemens Power Genration
Email: andy.paliszewski@siemens.com

Thomas Parish
University of Wyoming
Email: parish@uwyo.edu

David Parsons
NCAR
Email: parsons@ucar.edu

Edward (Ned) Patton
National Center for Atmospheric Research
Email: patton@ucar.edu

Gary Pawlas
University of Colorado at Boulder
Email: gary.pawlas@colorado.edu

Stanton Peterson
BP America
Email: stanton.peterson@bp.com

Franco Petrucci
Environment Canada
Email: franco.petrucci@ec.gc.ca

Rickey Petty
U.S Department of Energy - SC 23.3
Email: rick.petty@science.doe.gov

Yelena Pichugina
CIRES/CU Boulder/NOAA
Email: yelena.pichugina@noaa.gov

Robert Poore
Global Energy Concepts, LLC
Email: rpoore@globalenergyconcepts.com

Greg Poulos
Clipper Windpower
Email: gpoulos@clipperwind.com

Sara Pryor
Indiana University
Email: spryor@indiana.edu

Radian Belu
Desert Research Institute
Email: rbelu@dri.edu

Daran Rife
National Center for Atmospheric Research
Email: drife@ucar.edu

Mike Robinson
NREL
Email: mike_robinson@nrel.gov

Sven Schmitz
University of California Davis
Email: shschmitz@ucdavis.edu

Scott Schreck
NREL's National Wind Technology Center
Email: scott_schreck@nrel.gov

Marc Schwartz
National Renewable Energy Laboratory
Email: marc_schwartz@nrel.gov

George Scott
National Renewable Energy Laboratory
Email: george_scott@nrel.gov

Justin Sharp
PPM Energy, Inc.
Email: justin.sharp@ppmenergy.com

Will Shaw
Pacific Northwest National Laboratory
Email: will.shaw@pnl.gov

J. Charles Smith
UWIG
Email: jcharlessmith@comcast.net

James Sonnenmeier
Penn State Erie, The Behrend College
Email: jrs36@psu.edu

Brandon Storm
Texas Tech Univ.
Email: brandon.storm@ttu.edu

Peter Sullivan
National Center for Atmospheric Research
Email: pps@ucar.edu

Michael Susedik
Vaisala, Inc.
Email: mike.susedik@vaisala.com

Mikko Suuntala
Vaisala
Email: mikko.suuntala@vaisala.com

Eugene Takle
Iowa State University
Email: gstakle@iastate.edu

Peter Taylor
ESS, York University
Email: pat@yorku.ca

Leo Thesbjerg
Vestas Wind Systems A/S
Email: lt@vestas.com

Robert Thresher
NREL - National Wind Technology Center
Email: robert_thresher@nrel.gov

Kenneth Underwood
Atmospheric Systems Corporation
Email: ken@minisodar.com

Paul Veers
Sandia National Laboratories
Email: psveers@sandia.gov

Kenneth Waight
AWS Truewind
Email: ken@meso.com

Kevin Walter
TradeWind Energy, LLC
Email: kwalter@tradewindenergy.com

Thomas Warner
National Center for Atmospheric Research
Email: warner@ucar.edu

C. David Whiteman
University of Utah
Email: dave.whiteman@utah.edu

James Wilczak
NOAA/ESRL
Email: james.m.wilczak@noaa.gov

Ashley Williamson
DOE /SC
Email: ashley.williamson@science.doe.gov

Wei Yu
Environment Canada
Email: wei.yu@ec.gc.ca

Sharon Zhong
Michigan State University
Email: zhongs@msu.edu

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2008	Technical Report	June 2008

4. TITLE AND SUBTITLE
U.S. Department of Energy Workshop Report: Research Needs for Wind Resource Characterization

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Co-Chairs:
S. Schreck, J. Lundquist, and W. Shaw

5d. PROJECT NUMBER
NREL/TP-500-43521

5e. TASK NUMBER
WER7.0201

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-500-43521

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This workshop brought different atmospheric and wind technology specialists together to evaluate research needs for wind resource characterization.

15. SUBJECT TERMS
wind; characterization; meteorology; climatology; wind resource; atmospheric science; modeling; forecasting.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(09/2007)